# Experiment No. 4
The LM 741 Operational Amplifier

By: Prof. Gabriel M. Rebeiz
The University of Michigan
EECS Dept.
Ann Arbor, Michigan

The LM[*] 741 is the most widely used op-amp in the world due to its very low cost (<10 cents in bulk) and good, but not excellent, electrical characteristics. It is composed of 18 transistors integrated together on a tiny silicon chip. This silicon chip is inserted into an 8-pin or a 14-pin package with the connections shown below. Always refer to the ⌣ and/or ● signs. They indicate the location of pin #1.
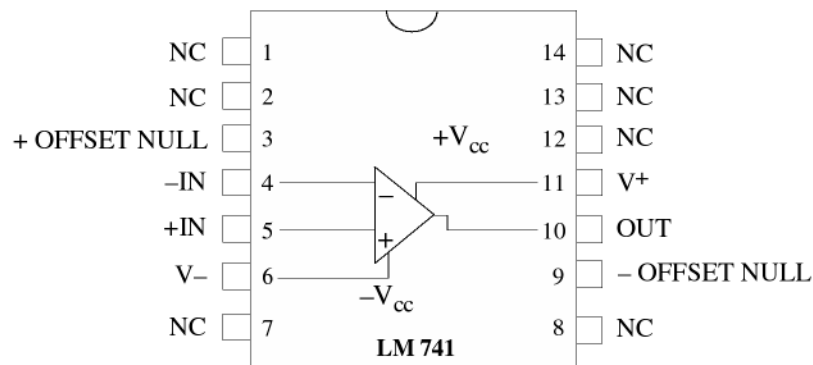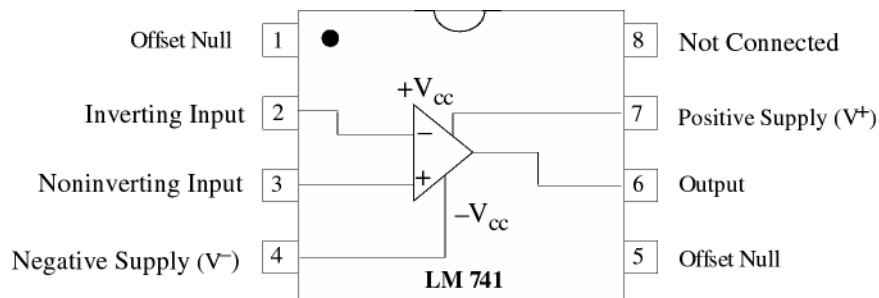
The essential electrical characteristics of the LM 741 op-amp are presented below.

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[*] LM is a trademark of National Semiconductor, Inc. The µA 741 was actually developed by Fairchild, Inc., one of the early and very successful electronic companies. However, they did not survive in the Silicon Valley man-eat-man atmosphere, and National Semiconductor bought Fairchild.

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Supply Voltage:	up to ± 12 V typ., ± 16V max.
Gain Bandwidth:	0.4–1.5 MHz (Gain = 1, BW = 1 MHz) Gain = 100, BW = 10 KHz)
Input Bias Current:	0.1–0.5 µA typical
Input Resistance:	2 MΩ typ.
Output Current:	25 mA max.
Output Resistance:	20 Ω typ.
Total Harmonic Distortion:	<0.2% at 1 KHz (in the linear region!)

The 741 op-amp is NOT suitable for driving speakers since the output current is limited to 25 mA. However, it is an excellent amplifier resulting in medium gain (20-100) for audio signals in the mV range. Of course, one can design 741 amplifier with a gain of 500, but then, the bandwidth will be limited to 2 kHz!

In the lab, you will be using the LM 747 chip, which contains two LM 741 op-amps in the same package. The pin configuration is:

National *Semiconductor*
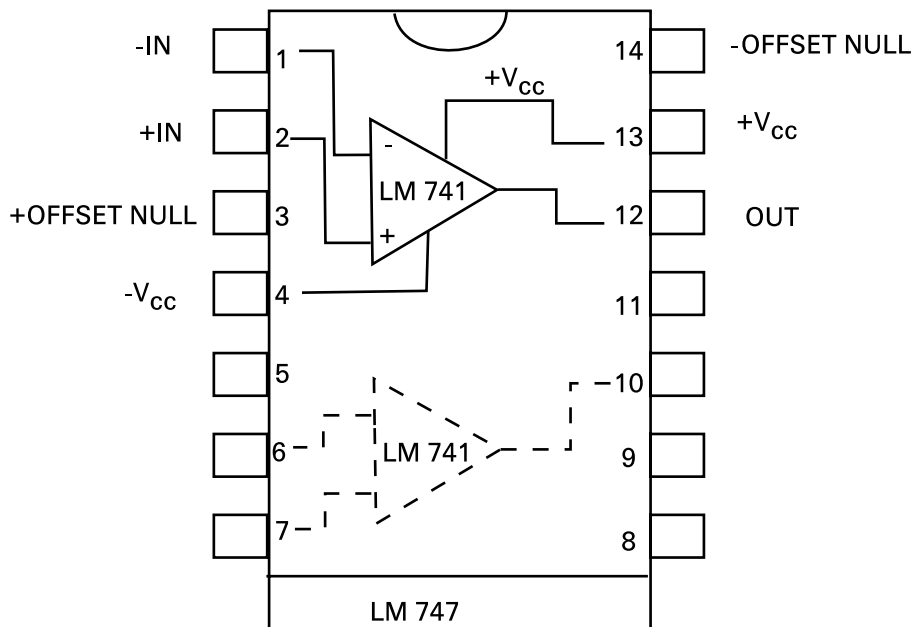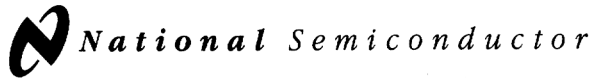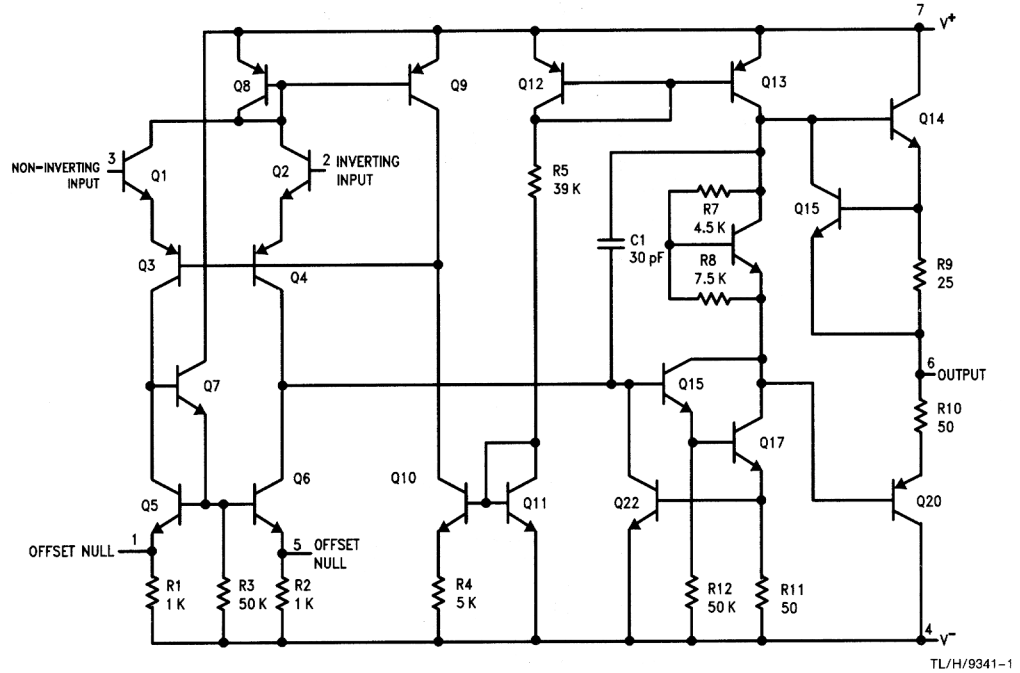
LM741 Operational Amplifier

General Description

The LM741 series are general purpose operational amplifiers which feature improved performance over industry standards like the LM709. They are direct, plug-in replacements for the 709C, LM201, MC1439 and 748 in most applications.

The amplifiers offer many features which make their application nearly foolproof: overload protection on the input and output, no latch-up when the common mode range is exceeded, as well as freedom from oscillations.
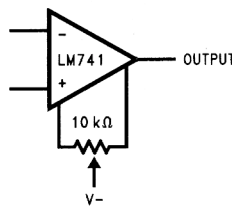
The LM741C/LM741E are identical to the LM741/LM741A except that the LM741C/LM741E have their performance guaranteed over a 0°C to +70°C temperature range, instead of −55°C to +125°C.

Schematic Diagram

TL/H/9341–1

Offset Nulling Circuit

TL/H/9341–7

Taken from *National Semiconductor–Operational Amplifiers Databook*, 1995 Edition.

Absolute Maximum Ratings

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/ Distributors for availability and specifications.
(Note 5)

	LM741A	LM741E	LM741	LM741C
Supply Voltage	±22V	±22V	±22V	±18V
Power Dissipation (Note 1)	500 mW	500 mW	500 mW	500 mW
Differential Input Voltage	±30V	±30V	±30V	±30V
Input Voltage (Note 2)	±15V	±15V	±15V	±15V
Output Short Circuit Duration	Continuous	Continuous	Continuous	Continuous
Operating Temperature Range	−55°C to +125°C	0°C to +70°C	−55°C to +125°C	0°C to +70°C
Storage Temperature Range	−65°C to +150°C	−65°C to +150°C	−65°C to +150°C	−65°C to +150°C
Junction Temperature	150°C	100°C	150°C	100°C
Soldering Information				
N-Package (10 seconds)	260°C	260°C	260°C	260°C
J- or H-Package (10 seconds)	300°C	300°C	300°C	300°C
M-Package				
Vapor Phase (60 seconds)	215°C	215°C	215°C	215°C
Infrared (15 seconds)	215°C	215°C	215°C	215°C

See AN-450 "Surface Mounting Methods and Their Effect on Product Reliability" for other methods of soldering surface mount devices.

ESD Tolerance (Note 6)	400V	400V	400V	400V

Electrical Characteristics (Note 3)

Parameter	Conditions	LM741A/LM741E			LM741			LM741C			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Input Offset Voltage	$T_A = 25°C$ $R_S \leq 10\ k\Omega$ $R_S \leq 50\Omega$		0.8	3.0		1.0	5.0		2.0	6.0	mV mV
	$T_{AMIN} \leq T_A \leq T_{AMAX}$ $R_S \leq 50\Omega$ $R_S \leq 10\ k\Omega$			4.0			6.0			7.5	mV mV
Average Input Offset Voltage Drift				15							$\mu V/°C$
Input Offset Voltage Adjustment Range	$T_A = 25°C, V_S = ±20V$	±10				±15			±15		mV
Input Offset Current	$T_A = 25°C$		3.0	30		20	200		20	200	nA
	$T_{AMIN} \leq T_A \leq T_{AMAX}$			70		85	500			300	nA
Average Input Offset Current Drift				0.5							nA/°C
Input Bias Current	$T_A = 25°C$		30	80		80	500		80	500	nA
	$T_{AMIN} \leq T_A \leq T_{AMAX}$			0.210			1.5			0.8	μA
Input Resistance	$T_A = 25°C, V_S = ±20V$	1.0	6.0		0.3	2.0		0.3	2.0		$M\Omega$
	$T_{AMIN} \leq T_A \leq T_{AMAX},$ $V_S = ±20V$	0.5									$M\Omega$
Input Voltage Range	$T_A = 25°C$							±12	±13		V
	$T_{AMIN} \leq T_A \leq T_{AMAX}$				±12	±13					V
Large Signal Voltage Gain	$T_A = 25°C, R_L \geq 2\ k\Omega$ $V_S = ±20V, V_O = ±15V$ $V_S = ±15V, V_O = ±10V$	50				50	200	20	200		V/mV V/mV
	$T_{AMIN} \leq T_A \leq T_{AMAX},$ $R_L \geq 2\ k\Omega,$ $V_S = ±20V, V_O = ±15V$ $V_S = ±15V, V_O = ±10V$ $V_S = ±5V, V_O = ±2V$	32 10			25			15			V/mV V/mV V/mV

Taken from *National Semiconductor–Operational Amplifiers Databook*, 1995 Edition.

Electrical Characteristics (Note 3) (Continued)

Parameter	Conditions	LM741A/LM741E			LM741			LM741C			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Output Voltage Swing	$V_S = \pm 20V$ $R_L \geq 10\ k\Omega$ $R_L \geq 2\ k\Omega$	± 16 ± 15									V V
	$V_S = \pm 15V$ $R_L \geq 10\ k\Omega$ $R_L \geq 2\ k\Omega$				± 12 ± 10	± 14 ± 13		± 12 ± 10	± 14 ± 13		V V
Output Short Circuit Current	$T_A = 25°C$ $T_{AMIN} \leq T_A \leq T_{AMAX}$	10 10	25	35 40		25			25		mA mA
Common-Mode Rejection Ratio	$T_{AMIN} \leq T_A \leq T_{AMAX}$ $R_S \leq 10\ k\Omega, V_{CM} = \pm 12V$ $R_S \leq 50\Omega, V_{CM} = \pm 12V$	80	95		70	90		70	90		dB dB
Supply Voltage Rejection Ratio	$T_{AMIN} \leq T_A \leq T_{AMAX}$, $V_S = \pm 20V$ to $V_S = \pm 5V$ $R_S \leq 50\Omega$ $R_S \leq 10\ k\Omega$	86	96		77	96		77	96		dB dB
Transient Response Rise Time Overshoot	$T_A = 25°C$, Unity Gain		0.25 6.0	0.8 20		0.3 5			0.3 5		μs %
Bandwidth (Note 4)	$T_A = 25°C$	0.437	1.5								MHz
Slew Rate	$T_A = 25°C$, Unity Gain	0.3	0.7			0.5			0.5		V/μs
Supply Current	$T_A = 25°C$					1.7	2.8		1.7	2.8	mA
Power Consumption	$T_A = 25°C$ $V_S = \pm 20V$ $V_S = \pm 15V$		80	150		50	85		50	85	mW mW
LM741A	$V_S = \pm 20V$ $T_A = T_{AMIN}$ $T_A = T_{AMAX}$			165 135							mW mW
LM741E	$V_S = \pm 20V$ $T_A = T_{AMIN}$ $T_A = T_{AMAX}$			150 150							mW mW
LM741	$V_S = \pm 15V$ $T_A = T_{AMIN}$ $T_A = T_{AMAX}$					60 45	100 75				mW mW

Note 1: For operation at elevated temperatures, these devices must be derated based on thermal resistance, and T_j max. (listed under "Absolute Maximum Ratings"). $T_j = T_A + (\theta_{jA}\ P_D)$.

Thermal Resistance	Cerdip (J)	DIP (N)	HO8 (H)	SO-8 (M)
θ_{jA} (Junction to Ambient)	100°C/W	100°C/W	170°C/W	195°C/W
θ_{jC} (Junction to Case)	N/A	N/A	25°C/W	N/A

Note 2: For supply voltages less than $\pm 15V$, the absolute maximum input voltage is equal to the supply voltage.

Note 3: Unless otherwise specified, these specifications apply for $V_S = \pm 15V$, $-55°C \leq T_A \leq +125°C$ (LM741/LM741A). For the LM741C/LM741E, these specifications are limited to $0°C \leq T_A \leq +70°C$.

Note 4: Calculated value from: BW (MHz) = 0.35/Rise Time(μs).

Note 5: For military specifications see RETS741X for LM741 and RETS741AX for LM741A.

Note 6: Human body model, 1.5 $k\Omega$ in series with 100 pF.

Taken from *National Semiconductor–Operational Amplifiers Databook*, 1995 Edition.

Experiment No. 4.
## Variable Gain Amplifiers; Summers; Intermodulation Products

Goal: To build and test a variable gain audio amplifier (100 Hz – 20 kHz), and then upgrade it to a two-channel summer. Also, to see the intermodulation products when two signals are fed into a non-linear amplifier.

❏ Read this experiment and answer the pre-lab questions before you come to the lab.

4.1 Variable Gain Audio Amplifier:

Equipment:
- Agilent E3631A Triple output DC power supply
- Agilent 33120A Function Generator
- Agilent 34401A Multimeter
- Agilent 54645A Oscilloscope

An inverting variable-gain amplifier suitable for audio frequencies is shown below:

$$V_{cc}^{+} = +12\ V$$
$$V_{cc}^{-} = -12\ V$$

$$R_a + R_b = 100\ k\Omega$$

Potentiometer
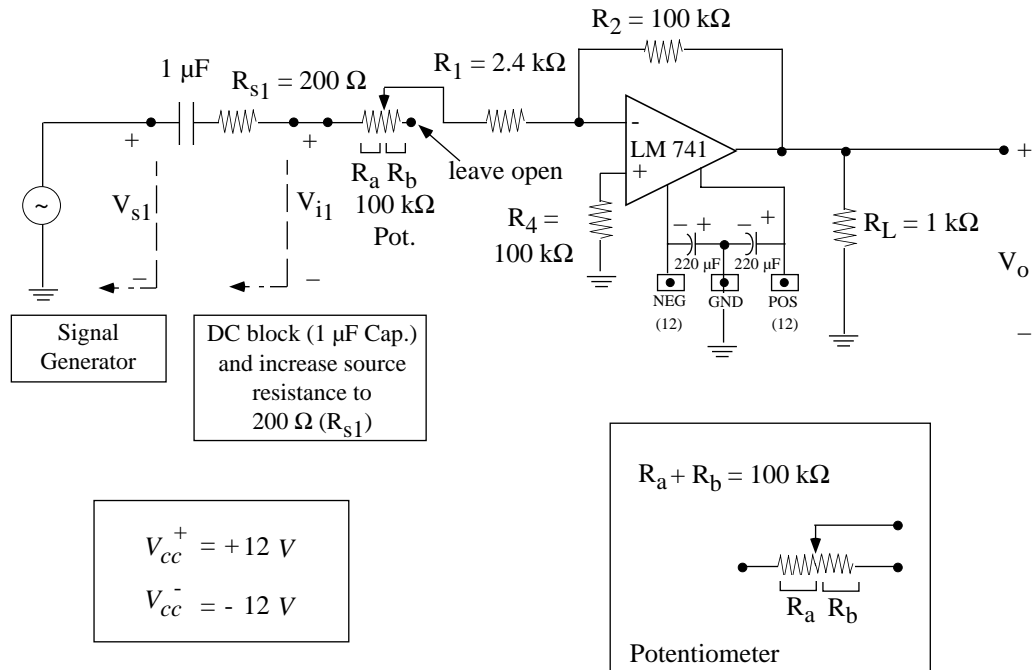
1. ❏ Draw the circuit in your notebook.

2. Assemble the circuit on the breadboard. When the circuit is ready, connect the cables to the power supply, but do <u>not</u> apply the voltage. Show your circuit to your lab instructor and he/she will check it and help you test it.

VARIABLE GAIN AMPLIFIER:

3. ❏ Measure the DC voltages V^-, V^+ and V_O. They should all be in the mV range.

4. Set the source at 1 kHz and V_S = 200 mV ppk and connect it to the amplifier. Connect V_{S1} to Channel 1 of the scope.

5. ❏ Connect V_O to Channel 2. Active Channel 2, measure Vppk (1) and Vppk (2). Vary the potentiometer from 0 Ω to 100 kΩ. Determine the minimum and maximum V_O. Determine the minimum and maximum gain (V_O/V_{S1}). Write down your results and calculations.

   Check to see if the experimental data agree with your pre-lab calculations (Gain from ~1to ~40). Check the frequency domain representation at both gain positions. Basically, if your amplifier is linear, and you are not clipping the output (amplifier saturation) then you should not observe any harmonics, ($2f_O$, $3f_O$, ...). Sketch the FFT spoectra, write a brief conclusion.

6. ❏ Measure the frequency response from 10 Hz to 1 MHz. Take data at 10, 20, 50, 100, 200, 500 Hz, 1, 2, 5, 10, 20, 50, 100, 200, 500 kHz, and at 1 MHz. At each frequency, measure V_i and V_O. Do these measurements for three gain settings: for the minimum gain setting ($|G| \sim 1$), maximum gain setting ($|G| \sim 40$) and for the midband gain setting of $|G| \sim 10$. Organize your data in a table form.

7. Something interesting happens for $|G| \approx 1$ (unity gain). You will have a +4-6 dB peak in the frequency response at ~200 KHz. This is due to the internal "compensation" capacitor (C_1 = 30 pF) which ensures stable operation of the op-amp under all negative feedback conditions. At unity gain, the interaction of C_1 with the transistors around it create this peak. This is advanced analog circuit design and you will see it in EECS 413. However, you can always say that you measured it first in EECS 210!

Congratulations; you have built a variable gain audio amplifier

with a gain of ~1-40 (0-32 dB).

4.2 Summer and Intermodulation Products:

1. Push the **Output/Off** button of the power supply to **Off** position (no voltage applied to your circuit). In a different (but close) part of the proto-board, connect the following circuit to the amplifier. The complete circuit is shown on the Experiment No.4 Worksheet.
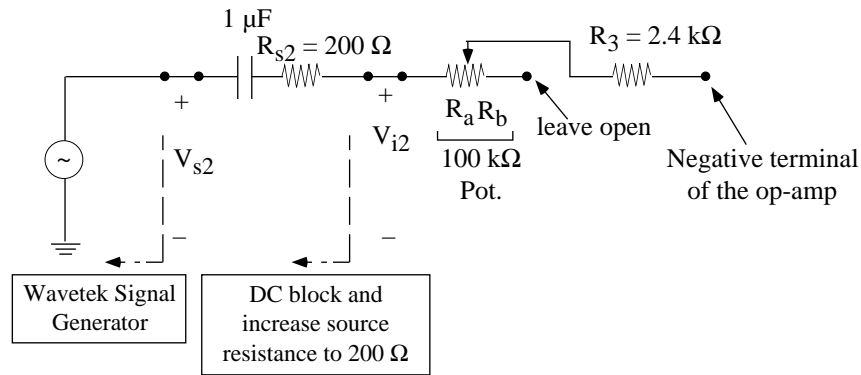
2. ❏ Redraw the entire circuit (with the op-amp) in your notebook.

3. Connect the output of the WAVETEK function generator to V_{s2} and set it at 800 Hz and V_{ppk} = 200 mV. Choose the gain of channel 2 to be around 10.

4. Connect the Agilent source to V_{s1} and set it at 1 kHz and V_{ppk} = 200 mV. Choose the gain of Channel 1 to be around 10.

2–CHANNEL SUMMER:

5. ❏ Now, turn on both sources and look at the output waveform. The output waveform closely resembles the telephone dial tone! Look at the frequency domain and see the output spectrum. Plot the spectrum of V_O (frequency domain). Again, if your amplifier is linear, then you should only measure f_1 (1 KHz) and f_2 (800 Hz), and no intermodulation products between the two signals ($2f_1$-f_2 , $2f_2$ -f_1, etc. ...).

6. Spend 5 minutes with the potentiometer (to vary the gain of each channel) and signal sources (to vary the frequency of each channel) to get any waveform you wish. You need not be adding only sinusoidal waves. You can try sine waves with triangular waves! However, make sure that you never drive the amplifier into clipping.

Congratulations, you have built a two-channel audio summer, called a "mixer", with a gain of 1-40 for each channel (0-32 dB).

INTERMODULATION PRODUCTS:

7. ❏ Disconnect the cables with T-connector from the Wavetek source. Increase the Agilent source voltage (V_{s1}) at f_1 = 1 kHz until you drive the amplifier well into clipping. A V_s around 0.65 V_{ppk} and maximum gain will be good. The output signal should have a fundamental frequency component of 17–18 dBV (at 1 kHz) and a third harmonic frequency component of around −10 dBV (at 3 kHz). Verify this using the scope in the FFT (frequency) domain. Choose a frequency span of 9.6 kHz.

8. ❏ Now, turn on the Wavetek source with V_{s2} = 200 mV_{ppk} and f_2 = 600 Hz and set the gain to 10. Notice the JUNGLE of frequencies which turn up. These are called

intermodulation products. Using the cursor, record the frequencies of components above the noise level. Verify if the following components are present in the spectrum:

f_1,
f_2,
$2f_1$,
$2f_2$,
$f_1 + f_2$,
$f_1 - f_2$,
$3f_1$,
$3f_2$,
$2f_1 - f_2$,
$2f_2 - f_1$,
$2f_1 + f_2$,
$2f_2 + f_1$.

Make a clear record of which components are above the noise level – and which ones are buried in the noise. If in doubt, as your lab instructor for help

Explanation:

The summer is the perfect circuit to see the intermodulation product between two tones in a non-linear circuit. Basically, if you have a circuit driven into non-linearity by a large input signal, then it will generate large amplitude harmonics. If a new but much smaller signal is fed into the amplifier, it will mix with all of the harmonics and will create a jungle of frequencies (see figure below).
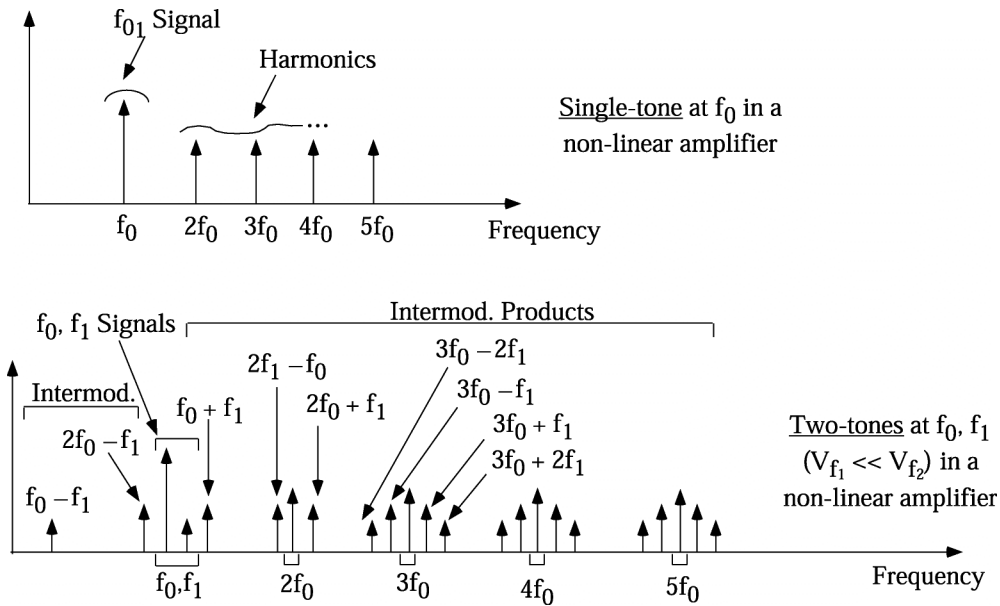
This example is only with two signals. Can you imagine what will happen if you have 3, 4, 5, ... signals? The simple answer is: HI-FI HELL. SO, THE GOLDEN RULE IS: NEVER DRIVE AN AMPLIFIER INTO THE NON-LINEAR REGION!

Experiment No. 4.
Variable Gain Amplifiers; Summers; Intermodulation Products

Pre-Lab Assignment

1. This question assumes an ideal op-am (Golden Rules apply): Calculate V_o/V_{i1}, V_{i1}/V_{s1}, and V_o/V_{s1} for the potentiometer set at $R_a = 0\ \Omega$ and $R_a = 100\ k\Omega$. Assume the 1 μF capacitor (DC block) to be a pure short circuit for your analaysis. YOU WILL NEED THIS FOR YOUR LAB.

These questions deal with the non-idealities of the LM 741 op-amp.

2. Why is the load resistor (R_L) of the LM 741 variable gain amplifier set at 1 kΩ? Calculate the max. output voltage swing if $R_L = 200\ \Omega$.

3. The LM 741 is connected to a DC source of ±12 V with $R_L = 1$ kΩ. What is the maximum swing (approximately) of V_o before clipping occurs? If $R_L = 1$ kΩ, what is the maximum power that can be delivered to the load ($P_L = V_{pk}^2/2R_L = V_{rms}^2/R_L$).

4. You will notice on in Experiment #4 that there is a 100 kΩ resistor connected between the ground and the positive (non-inverting) input of the LM 741 amplifier. Can you explain why this is done? (See Lab #5 Introduction). Also, why 100 kΩ and not 5 kΩ or 500 kΩ?

Experiment No. 4.
Variable Gain Amplifiers; Summers; Intermodulation Products

Lab-Report Assignment

1. Plot the frequency response of the inverting amplifier for the low, medium, and high gain (V_O/V_{S1}) settings on the same graph using MATLAB. Use a dB scale for the gain and a logarithmic-scale for frequency. Explain your results.

2. Calculate the Gain•Bandwidth product at each gain setting. Do your calculations agree with what you expect? Explain.

Design:

3. Design a variable gain amplifier with a maximum gain of ~100 and a minimum gain of ~0.5. You can use resistances up to 100 kΩ and a 0-200 kΩ potentiometer. An input resistance of 1 kΩ or above is required.

4. For the amplifier/summer on page 65, assume R_{S1} = 10 kΩ and R_{S2} = 1 kΩ. What is the max./min. gain for V_O/V_{S1}? What is the max./min. gain for V_O/V_{S2}?

    As you can see, there is a resistive divider occurring between R_{S1} and ($R_1 + R_a$), and between R_{S2} and ($R_3 + R_a$). Draw a circuit which ensures that both channels have <u>exactly</u> the same gain even if they have different source resistances (you can use other op-amps if you wish). You <u>cannot</u> use potentiometers in your design.

Intermodulation Products:

5. In the lab report of Experiment #3, you calculated the harmonics generated by a non-linear amplifier. Now, you are going to calculate how intermodulation products occur in non-linear amplifiers. A non-linear amplifier transfer function is given by:

    $V_O = A\, V_i + ß\, V_i^2 + \gamma\, V_i^3$ where $A \equiv$ gain of amplifier

                                     $ß, \gamma \equiv$ non-linear components

    and

    $V_i = V_1 \cos(\omega_1 t) + V_2 \cos(\omega_2 t)$ $ß, \gamma \ll A$

    with $V_2 \ll V_1$.

    a. Calculate $V_O(t)$ (neglect all components of V_2^2 and V_2^3 since they are very small). Put V_O in the form: $V_O = A \{ ... \} + ß \{ ... \} + \gamma \{ ... \}$.

        As a result of your calculation, you should get rid of all powers, such as $\cos^2(\omega t)$, replacing them with various harmonics such as $\cos(2\omega t)$; get rid of the products, such as $\cos(\omega_1 t) \cdot \cos(\omega_2 t)$ replacing them with intermodulation products such as $\cos((\omega_1 + 2\omega) t)$, $\cos((\omega_1 - \omega_2) t)$. Use trigometric formulas such as mentioned on p. 51 of this Manual.

b.   Draw the output spectrum in dB for:

$V_1 = 0.2\ V_{rms}$,

$V_2 = 0.01\ V_{rms}$,

$f_1 = 1\ kHz$,

$f_2 = 1.1\ kHz$,

$A = 40$,

$ß = 4$,

$\gamma = 1$.

You can simply sketch this spectrum – or you can plot it with MATLAB, using <u>stem</u> command.

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Worksheet/Notes