Department of Mechanical Engineering

To: Dr. Dieckman September 28, 2022
From: Semih Akyuz, Raymond Pagan Jr.
Re: Cutoff Frequency of LM741 Through Relation of Base & Amplified Sine Wave

Amplitude readings of a non-amplified and an inversely amplified sine wave were manually collected on a digital oscilloscope through varying frequencies supplied by a wave generator. The experimental cutoff frequency of the LM741 op-amp was 89.2 kHz $\pm$ 0.7 kHz with a 18.9% error in comparison to the expected cutoff frequency of 75kHz. Manual data collection is predicted to be a cause of error due to reliance on visual estimations. Figure 1. shows the trendline equation of the experimental data which was used to find its intersection with the theoretical -3 dB line to determine the cutoff frequency.

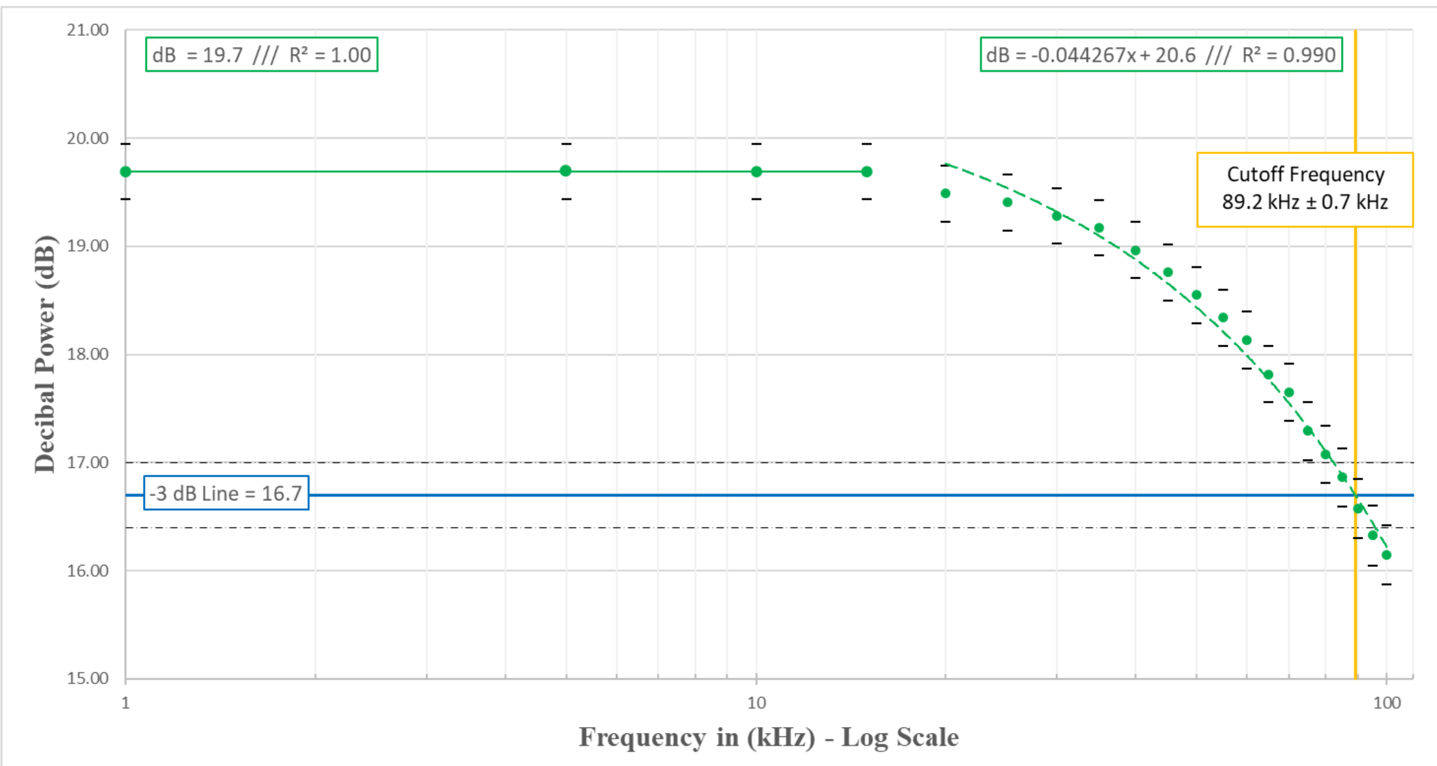

Figure 1. The cutoff frequency for the LM741 op-amp was determined to be 89.2 kHz $\pm$ 0.7 kHz at the intersection of the experimental trend line and the -3 dB line which is an 18.9% error compared to the expected cutoff frequency of 75kHz.

An Agilent 33220A wave generator was used to create a sine wave at frequencies ranging from 1kHz to 100kHz in 5kHz increments. A Tektronix TBS 1052B digital oscilloscope simultaneously received the unmodified wave and an amplified wave through the LM741 op-amp as shown in the 'Experimental Setup Attachment'. The op-amp circuit was created using pin locations as shown in its data sheet [1]. The offset pins of the op-amp were wired to a Keysight E3631A DC power supply providing $\pm$15 volts. To ensure fitting, scaling on the oscilloscope was set to 20mV and 200mV for the unmodified and amplified waves respectively. The scaling was carried through calculations accordingly. Peak to peak amplitudes of the two waves were obtained visually to find the gain value as shown in the 'Calculations Attachment'. Decibel power (dB) as a function of frequency in (kHz) was plotted to determine the cutoff frequency.

[1] Real Analog, Chapter 5 "Section 5.3, Commercially Available Operational Amplifiers" *Figure 5.11*

The bandwidth -*GBP*- and the voltage gain -A_v- of the LM741 were used to calculate the expected cutoff frequency -*f*- (Equation 1). The gain was calculated where A_{out} is the amplitude of the inversely amplified wave and A_{in} is the amplitude of the raw wave (Equation 2). The experimental cutoff frequency was then calculated by finding at which frequency the gain is less than 3 dB of the original value.

$$f = GBP \,/\, A_v \tag{1}$$

$$Gain\ (dB) = 20log\left(\frac{A_{out}}{A_{in}}\right) \tag{2}$$

The values were split into two sets with individual linear trendlines. The splitting point of the data was determined by optimizing the R^2 values of each trendline. The split resulting in the highest average R^2 value between the two lines was found to be 4 points on set 1 and 17 points on set 2. The associated table and a further explanation is provided in the 'R^2 Optimization Attachment'.

Uncertainty in the experiment was caused by the manual collection of the data through visually estimating the cursor placement of the oscilloscope on the peaks of the two waves. The non-amplified wave had a bias uncertainty of ±1 mV while the inversely amplified wave had a bias uncertainty of ±10 mV. Duplicating the calculations using the maximum and minimum values of the two amplitudes provided two more sets of data. Their trendlines were used to find the minimum and maximum values of the cutoff frequency which was used as the positive and negative uncertainty associated with the experimental result.

The experimental cutoff frequency of the LM741 op-amp was found to be 89.2 kHz $\pm$ 0.7 kHz with a 18.9% error compared to the expected cutoff frequency of 75 kHz. The results can be improved by using the peak reading on the oscilloscope rather than visually estimating the peaks of the sin waves.

Attachments: Calculations, Uncertainty, R^2 Optimization, Experimental Setup

CALCULATIONS

Expected Cutoff Frequency

$$f = \frac{GBP}{A_v}$$

where

f is the cutoff frequency of the op-amp
GBP is the bandwidth of the op-amp provided in documentation
A_v is the voltage gain of the op-amp provided in documentation

Gain dB

$$Gain\ dB\ = 20log\left(\frac{A_{out}}{A_{in}}\right)$$

where

$Gain\ dB$ is the gain of the op-amp at the amplitude ratio for each point of data
A_{out} is the amplitude of the inversely amplified wave in mV
A_{in} is the amplitude of the non-amplified wave in mV

Frequency - (Ex. Using Experimental Line)

$$dB\ Power = -0.044(f\ kHz) + 20.6$$

where

$dB\ Power$ is the initial power minus 3 dB, which intersects the cutoff frequency on the given line
$f\ kHz$ is the cutoff frequency for the given set of data

UNCERTAINTY ATTACHMENT

Gain Maximum - (Gain dB + U_{+xb})

$$\mathbf{Gain\ dB + U_{+xb} = 20log\left(\frac{A_{out} + \boldsymbol{U_{bo}}}{A_{in} - \boldsymbol{U_{bi}}}\right)}$$

where

$Gain\ dB + U_{+xb}$ is the maximum experimental gain at a point with uncertainty
A_{out} is the amplitude of the inversely amplified wave in mV
A_{in} is the amplitude of the non-amplified wave in mV
U_{bo} is the bias uncertainty of the inversely amplified sin wave
U_{bi} is the bias uncertainty of the non-amplified sin wave

Gain Minimum - (Gain dB – U_{-xb})

$$\mathbf{Gain\ dB - U_{-xb} = 20log\left(\frac{A_{out} - \boldsymbol{U_{bo}}}{A_{in} + \boldsymbol{U_{bi}}}\right)}$$

where

$Gain\ dB - U_{-xb}$ is the minimum experimental gain at a point with uncertainty
A_{out} is the amplitude of the inversely amplified wave in mV
A_{in} is the amplitude of the non-amplified wave in mV
U_{bo} is the bias uncertainty of the inversely amplified sin wave
U_{bi} is the bias uncertainty of the non-amplified sin wave

Gain Positive Uncertainty

$$\boldsymbol{U_{+xb}} = \mathbf{(Gain\ dB + U_{+xb}) - Gain\ dB}$$

where

$Gain\ dB$ is the experimental gain at the given point
U_{+xb} is the positive offset uncertainty of the experimental gain

Gain Negative Uncertainty

$$\boldsymbol{U_{-xb}} = \mathbf{Gain\ dB - (Gain\ dB - U_{-xb})}$$

where

$Gain\ dB$ is the experimental gain at the given point
U_{-xb} is the negative offset uncertainty of the experimental gain

Minimum and Maximum Cutoff Frequencies – Calculated w/ Excel Solver

	Cutoff Frequency (kHz)	dB @ Intersection
Cutoff Min	88.4	17.0
Cutoff	89.2 ± 0.7	16.7
Cutoff Max	89.8	16.4

R^2 OPTIMIZATION

This attachment shows the method used to find the optimal split position for the experimental line dB vs log(frequency). The goal is to maximize the average R^2 value to achieve the most accurate combination of trend lines for the initial and curved part of the data. The table below shows the R^2 values of the trendlines formed with each variation of the split location and highlights the highest average R^2 value. The analysis resulted in a 4 to 17 split for the 21 total data points.

Points in L1	Points in L2	R^2 of L1	R^2 of L2	R^2 Average
3	18	1	0.9879	0.99395
4	17	1	0.9896	0.9948
5	16	0.5201	0.9936	0.75685
6	15	0.732	0.996	0.864
7	14	0.8311	0.9977	0.9144
8	13	0.8864	0.9978	0.9421
9	12	0.904	0.998	0.951
10	11	0.9127	0.9979	0.9553
11	10	0.921	0.9975	0.95925
12	9	0.9293	0.9966	0.96295
13	8	0.9372	0.9958	0.9665
14	7	0.9377	0.994	0.96585
15	6	0.9448	0.9964	0.9706
16	5	0.9452	0.9945	0.96985
17	4	0.9492	0.9891	0.96915
18	3	0.9542	0.9901	0.97215

EXPERIMENTAL SETUP