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Faculty of Engineering, Built Environment and Information Technology

ENE310

FILTER DESIGN

PRACTICAL 2

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A.3 Designers need to choose between topologies when implementing their filters. What are some reasons that a designer may choose a Multiple Feedback filter over a KRC filter? 61

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1 Introduction

Filter design is an important process for deigning unique high quality filters. The designer is able to create and optimize the filter based on the topology and hyper parameters it is made up of. The different design parameters require optimisation and fine tuning to maximise the design goals and to compensate for physical deficiencies which may exist. The design process and parameters are investigated.

2 Design objectives

Design two eighth order filters. One where a second order filter is copy and pasted (CP) four times to make an eighth order system. The second is designed using cascaded design with frequency and quality factor scaling. The filter is required to be a Bessel filter with a cutoff (design) frequency of 56.8KHz. The topology of the circuit must be researched and chosen (KRC, Multifeedback). The quality factor and frequency may then be observed from the simulations. The component tolerances must be investigated with different resistor and capacitor standards. The hyper parameters such as the quality may be affected by the component tolerance. Monte Carlo may also be used to investigate the tolerances. Physical op-amps are also investigated to simulate affects the likes of voltage offset and gain bandwidth product on the filter and it's response.

3 Detail Design

3.1 Design Choice

A multifeedback low pass filter was chosen for design and synthesis. The multifeedback topology allows potentially easier manipulation of the quality factor (Q) and gain at the expense of more components. Multifeedback circuit's also do not lose accuracy as fast as sallen-key circuits do at higher gains. A gain of ten is chosen for the design. Multifeedback circuits are also less sensitive to component changes (variance) which is beneficial when the tolerance of the component is unpredictable. At higher Q values the sallen-key may ripple more than the multifeedback around the resonance frequency. Albeit a Bessel filter is being designed for thus an extremely high Q will be required for any ripple to exist.

Sallen-keys however do possess more accuracy around the cut-off frequency. They will begin to attenuate closer to the value than a multifeedback would. However Bessel as it is normalized to be cascaded it loses a bit of accuracy around the cut off frequency as well. The KRC also possess a lower noise gain than the multifeedback at lower frequencies.

The trade-off of a slightly less accurate low pass with multifeedback around the design frequency but better scaling with Q, and the gain due to more customization with components deems multifeedback as the choice for the design. The noise gain may be reduced into the circuit through physical measures such as buffers, shorter wires and the ordering of the cascade discussed further in the report.

3.2 Transfer function

The low pass transfer function of a second order circuit is given[1]:

$$H(jf) = \frac{H_0}{1 - (\frac{f}{f_c})^2 + (\frac{jf}{f_c})/Q} \tag{1}$$

The function is realized within python, code is attached in appendix B.

3.3 Second order Copy paste

From the cascade design table for a second order Bessel filter cascaded through copy and pasting (CP) to an eigth order:
Q = 0.577
f_{scale} = 1.274

$$H_{CP}(jf) = \left(\frac{H_0}{1 - (\frac{f}{f_{scale}*f_c})^2 + (\frac{jf}{f_{scale}*f_c})/Q}\right)^4 \tag{2}$$

The transfer function is multiplied by itself four times in identical cascaded design.

3.4 Eight order from cascaded design

Table of the different scaling frequencies and quality factors for each stage of eighth order Bessel:

Stage (n)	$f_{scale-n}$	Q_n
1	1.784	0.506
2	1.838	0.560
3	1.958	0.711
4	2.196	1.226

The transfer function follows the form of a second order above with each function being a stage with different Q and scaling frequencies:

$$\begin{aligned} H(jf) = &\left(\frac{\sqrt[4]{H_0}}{1 - (\frac{f}{f_{scale-1}*f_c})^2 + (\frac{jf}{f_{scale-1}*f_c})/Q_1}\right) * \left(\frac{\sqrt[4]{H_0}}{1 - (\frac{f}{f_{scale-2}*f_c})^2 + (\frac{jf}{f_{scale-2}*f_c})/Q_2}\right) * \\ &\left(\frac{\sqrt[4]{H_0}}{1 - (\frac{f}{f_{scale-3}*f_c})^2 + (\frac{jf}{f_{scale-3}*f_c})/Q_3}\right) * \left(\frac{\sqrt[4]{H_0}}{1 - (\frac{f}{f_{scale-4}*f_c})^2 + (\frac{jf}{f_{scale-4}*f_c})/Q_4}\right) \end{aligned} \tag{3}$$

3.5 Multifeedback implementation

3.5.1 Design equations

The equations are applied in the following order to derive components values:
Determining the capacitance spread value n:

$$n \geq 4 * Q^2(1 + H_0) \tag{4}$$

Choosing capacitor values such that:

$$n = \frac{C_1}{C_2} \tag{5}$$

R_3 may then be found:

$$R_3 = \frac{1 + \sqrt{1 - 4 * Q^2 * (1 + H_0)/n}}{2 * \omega_0 * Q * C_2} \tag{6}$$

and subsequently R_1 and R_2:

$$R_1 = \frac{R_3}{H_0} \tag{7}$$

$$R_2 = \frac{1}{\omega_0^2 * R_3 * C_1 * C_2} \tag{8}$$

Smaller values for C_1 and C_2 allow for larger values for the resistors which prevents excessive power draw from small resistances and large currents.

3.6 Ideal component design

The formulae above used in conjunction with the design frequency, frequency scaling factors, and Q are used to design an ideal filter realization. The ideal filter realizations do not use any set component standard. Raw numerical values are used for each component where possible.
The design frequency is 56.8KHz and a value of 100 pico-farads for capacitor C_2 is chosen.

3.6.1 Copy and paste second order filter

The gain is spread evenly among each stage as each stage is a duplicate.

Table showing ideal values of copy and paste filter:

H0	Fn	Q	n_chosen	C1	C2	R1	R2	R3
1.778	1.274	0.577	3.699	3.699E-10	1.0E-10	1.07E+04	6.86E+03	1.91E+04
1.778	1.274	0.577	3.699	3.699E-10	1.0E-10	1.07E+04	6.86E+03	1.91E+04
1.778	1.274	0.577	3.699	3.699E-10	1.0E-10	1.07E+04	6.86E+03	1.91E+04
1.778	1.274	0.577	3.699	3.699E-10	1.0E-10	1.07E+04	6.86E+03	1.91E+04

3.6.2 Cascaded second order filter

Gain is also spread between each stage evenly.

Table showing ideal values of cascaded filter:

H0	Fn	Q	n_chosen	C1	C2	R1	R2	R3
1.778	1.784	0.506	2.845	2.845E-10	1.000E-10	8.73E+03	5.59E+03	1.55E+04
1.778	1.838	0.56	3.485	3.485E-10	1.000E-10	7.65E+03	4.90E+03	1.36E+04
1.778	1.958	0.711	5.617	5.618E-10	1.000E-10	5.66E+03	3.62E+03	1.01E+04
1.778	2.196	1.226	16.703	1.670E-09	1.000E-10	2.93E+03	1.87E+03	5.20E+03

3.6.3 LTspice ideal copy-paste filter diagram

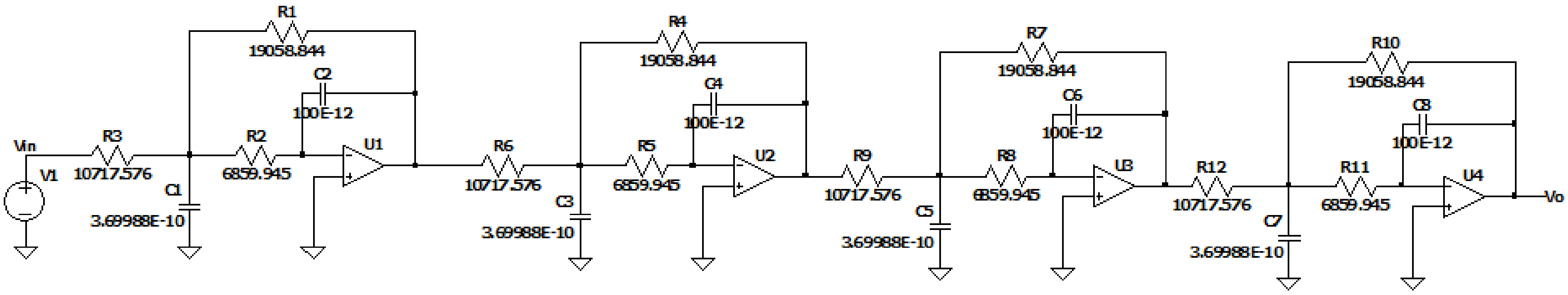

Figure 1: Ideal copy-paste filter diagram

3.6.4 LTspice ideal cascade filter diagram

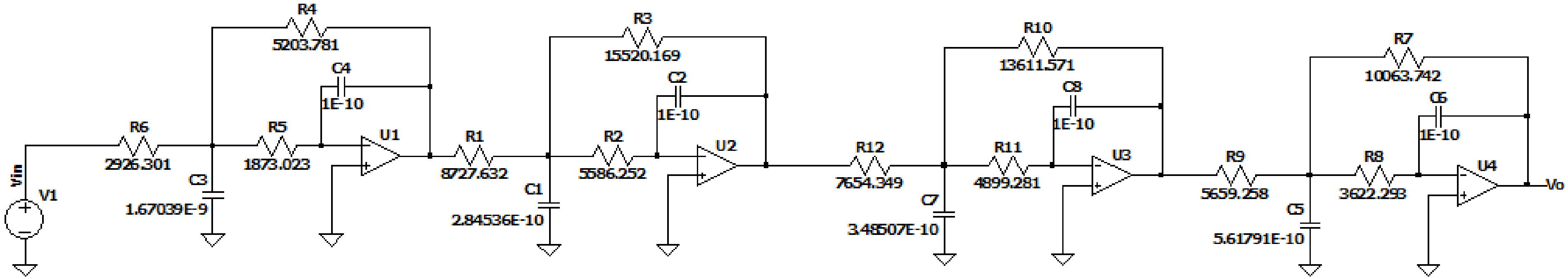

Figure 2: Ideal cascade filter diagram

3.7 E6/E12 Resistor and Capacitor component design

The values from the ideal component design tables are approximated with real world components using the E6 resistor and E12 Capacitor standards.

3.7.1 Copy and paste second order filter

Table showing E6/E12 values of copy and paste filter:

C1	C2	R1	R2	R3
3.60E-10	1E-10	1.00E+04	6.81E+03	1.91E+04
3.60E-10	1E-10	1.00E+04	6.81E+03	1.91E+04
3.60E-10	1E-10	1.00E+04	6.81E+03	1.91E+04
3.60E-10	1E-10	1.00E+04	6.81E+03	1.91E+04

3.7.2 Cascaded filter

Table showing E6/E12 values of cascaded filter:

C1	C2	R1	R2	R3
2.70E-10	1E-10	1.00E+04	4.70E+03	1.50E+04
3.30E-10	1E-10	6.80E+03	4.70E+03	1.50E+04
5.60E-10	1E-10	4.70E+03	3.30E+03	1.00E+04
1.80E-09	1E-10	3.30E+03	2.20E+03	4.70E+03

3.7.3 LTspice E6/E12 copy-paste filter diagram

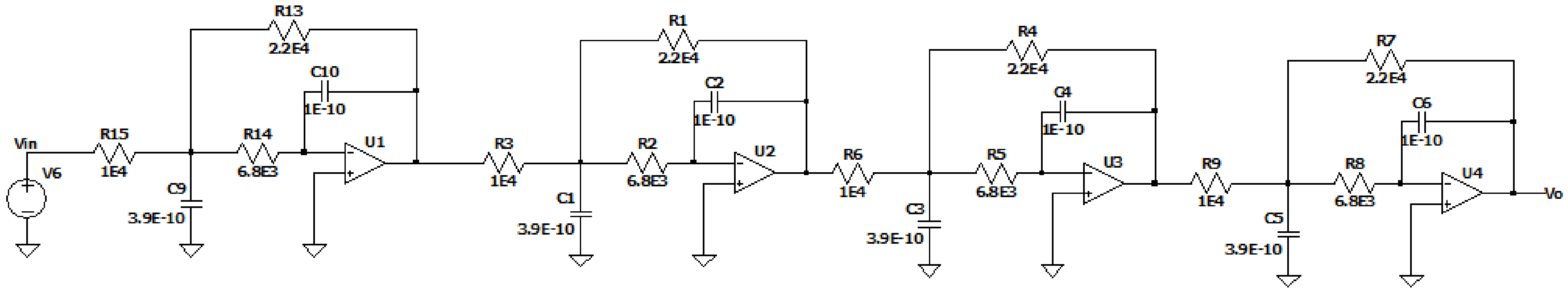

Figure 3: Ideal copy-paste filter diagram

3.7.4 LTspice E6/E12 cascade filter diagram

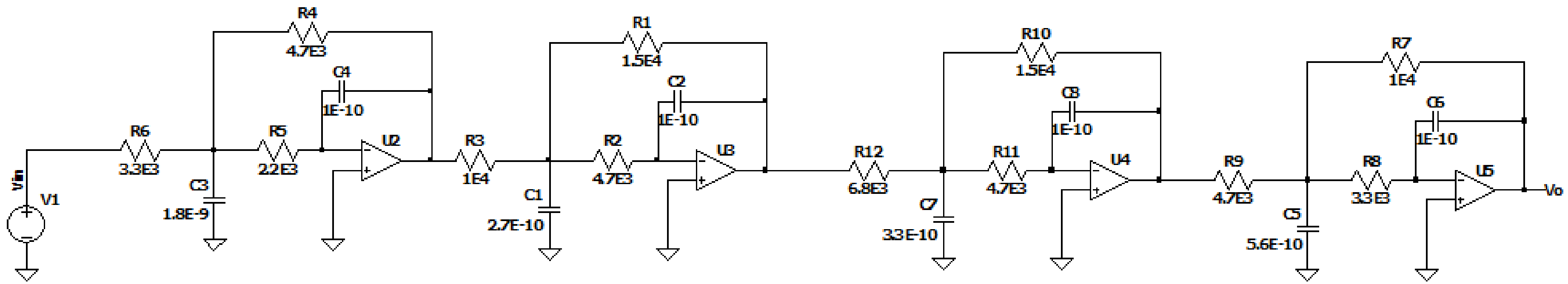

Figure 4: Ideal cascade filter diagram

3.8 Alternate tolerance: E96/E24 Resistor and Capacitor component design

In addition to the E6/E12 standard, the values from the ideal component design tables are approximated with real world components using the E96 resistor and E24 Capacitor standards. These values are used in conjunction with non ideal op-amps for testing.

3.8.1 Copy and paste second order filter

Table showing E6/E12 values of copy and paste filter:

C1	C2	R1	R2	R3
3.90E-10	1E-10	1.00E+04	6.80E+03	2.20E+04
3.90E-10	1E-10	1.00E+04	6.80E+03	2.20E+04
3.90E-10	1E-10	1.00E+04	6.80E+03	2.20E+04
3.90E-10	1E-10	1.00E+04	6.80E+03	2.20E+04

3.8.2 Cascaded filter

Table showing E6/E12 values of cascaded filter:

C1	C2	R1	R2	R3
2.70E-10	1E-10	1.00E+04	4.70E+03	1.50E+04
3.30E-10	1E-10	6.80E+03	4.70E+03	1.50E+04
5.60E-10	1E-10	4.70E+03	3.30E+03	1.00E+04
1.80E-09	1E-10	3.30E+03	2.20E+03	4.70E+03

3.8.3 LTspice E96/E24 copy-paste filter diagram

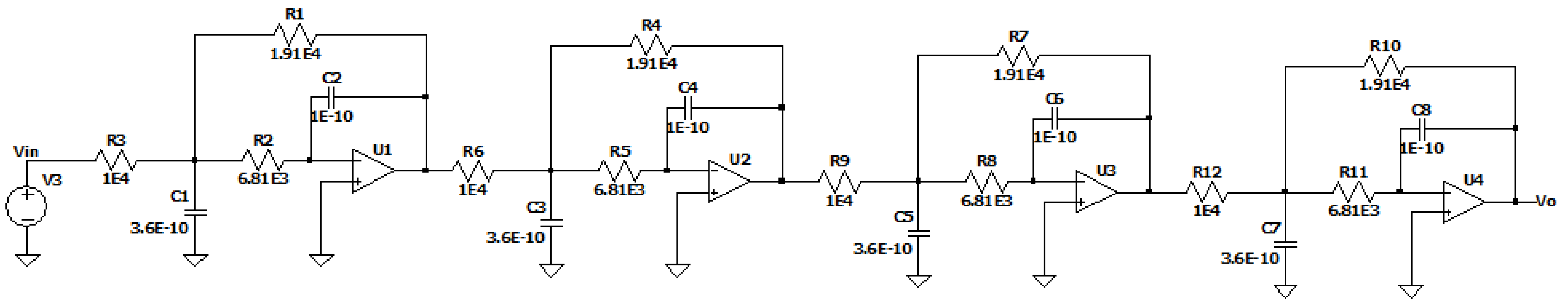

Figure 5: Ideal copy-paste filter diagram

3.8.4 LTspice E96/E24 cascade filter diagram

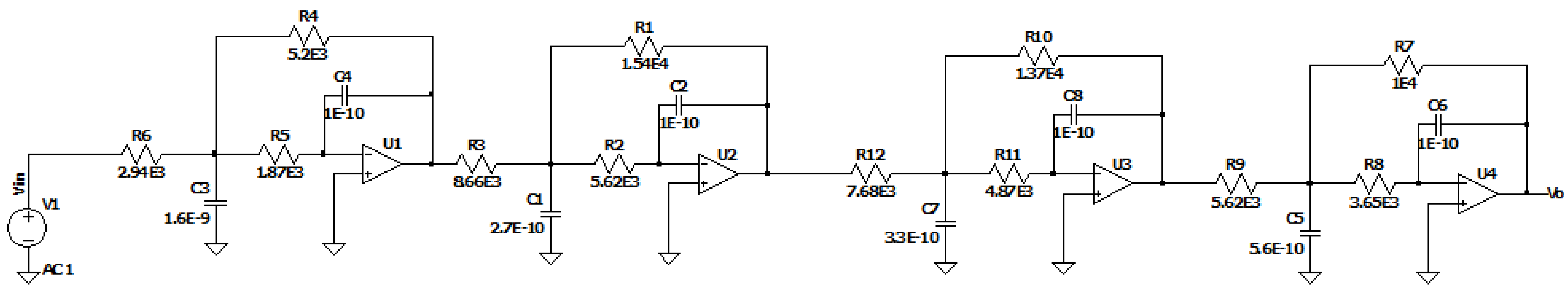

Figure 6: Ideal cascade filter diagram

3.9 Op-amp considerations

Two operational amplifier designs are considered within the investigation for component variations:

1. Ideal universal op-amp for ideal and single parameter testing considerations:
   - Gain bandwidth product is fixed at 10MHz
   - Voltage off-set is set to zero
   - Slew rate 10MHz
2. LF347 op-amp for practical-real-life considerations
   - Gain bandwidth product is 4MHz
   - Voltage off-set is given as 5mV typically
   - 8V/μs
3. Additionally the MCP604's frequency response is observed
   - Gain bandwidth product is 10MHz
   - Voltage off-set is given as 5μV typically

3.10 Non-ideal circuits

The E24/E96 resistor and capacitor standard circuit used in conjunction with the MCP604 and LF347 op-amps for non-ideal simulations.

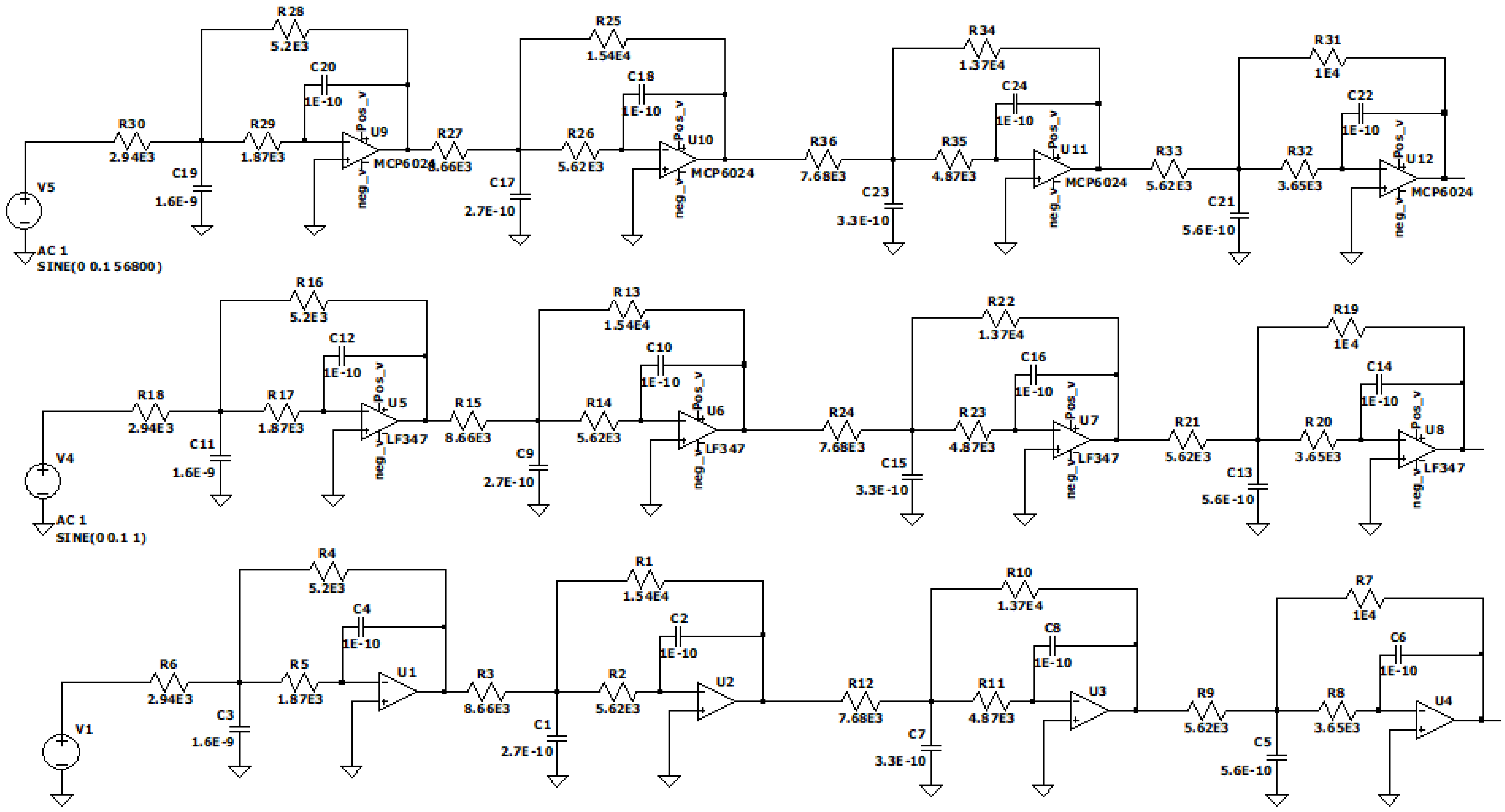

Figure 7: MCP604 (top), LF347 (middle), Ideal (bottom) filter circuit diagrams

4 Results and simulations

4.1 Copy-paste transfer function

4.1.1 Transfer function amplitude response of copy-paste filter

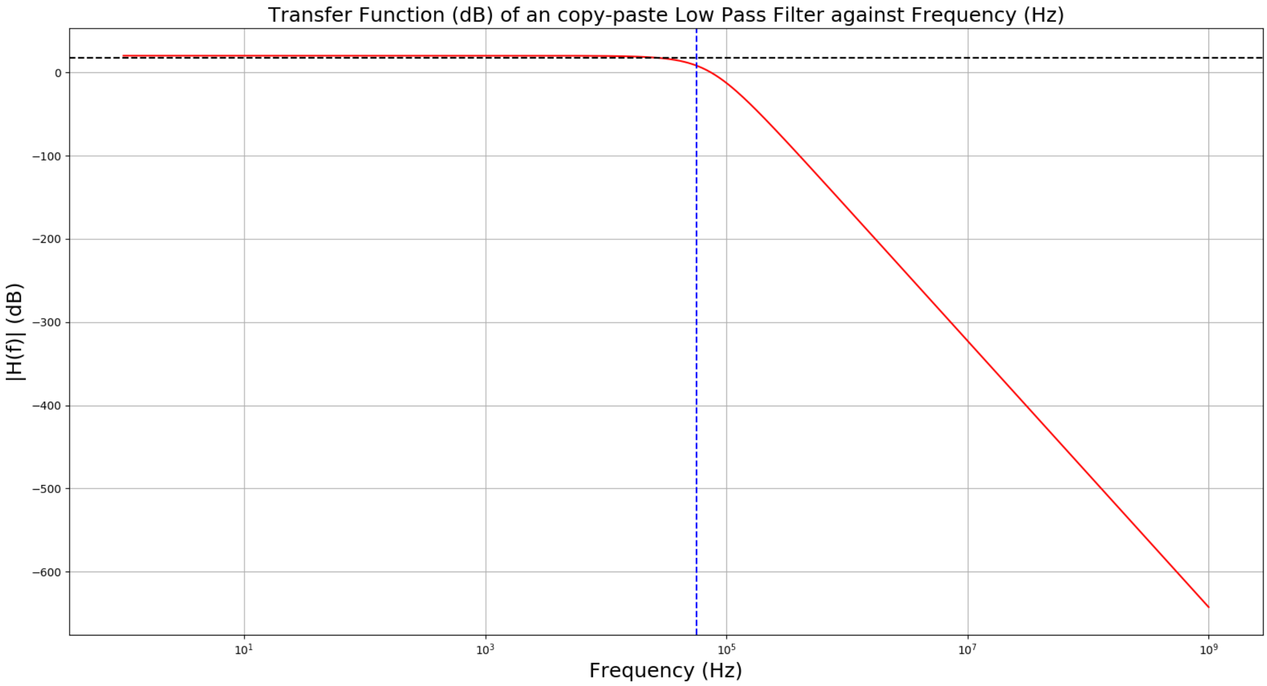

Figure 8: Copy-paste python simulation

4.1.2 Copy-paste cut off and design frequency

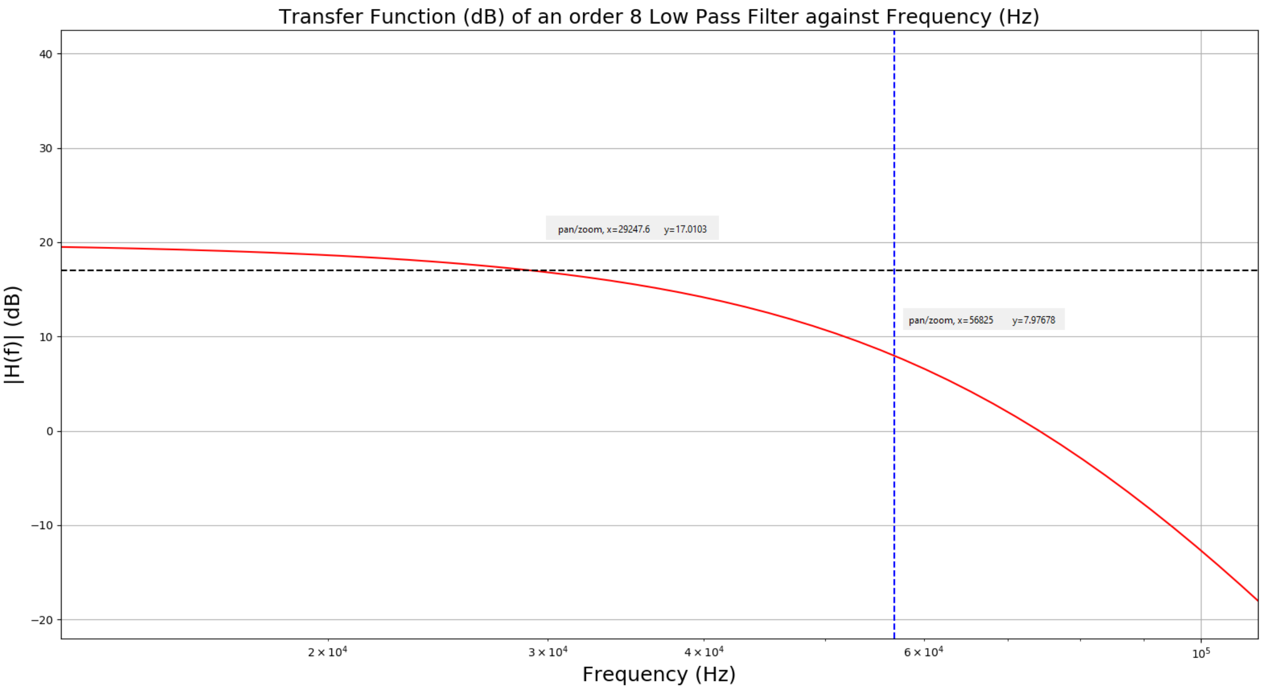

Figure 9: Copy-paste cut-off and design frequency

4.2 Cascaded transfer function

4.2.1 Transfer function amplitude response of cascaded filter

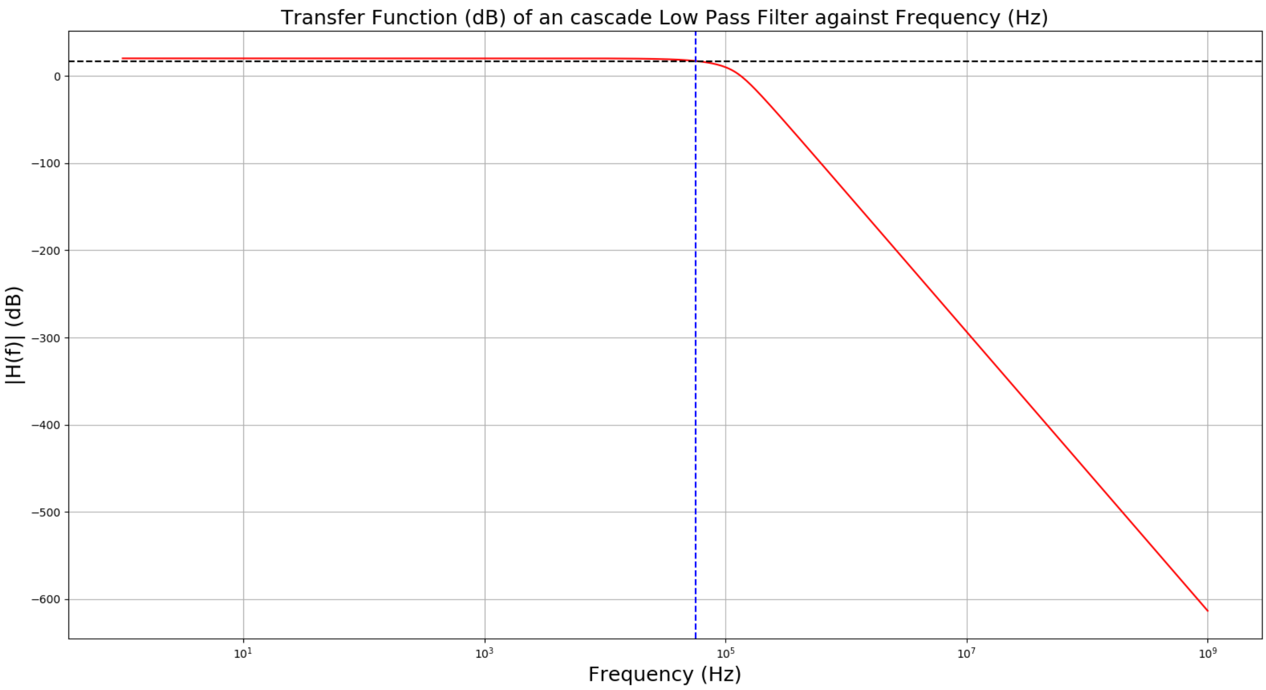

Figure 10: Cascade python simulation

4.2.2 Copy-paste cut off and design frequency

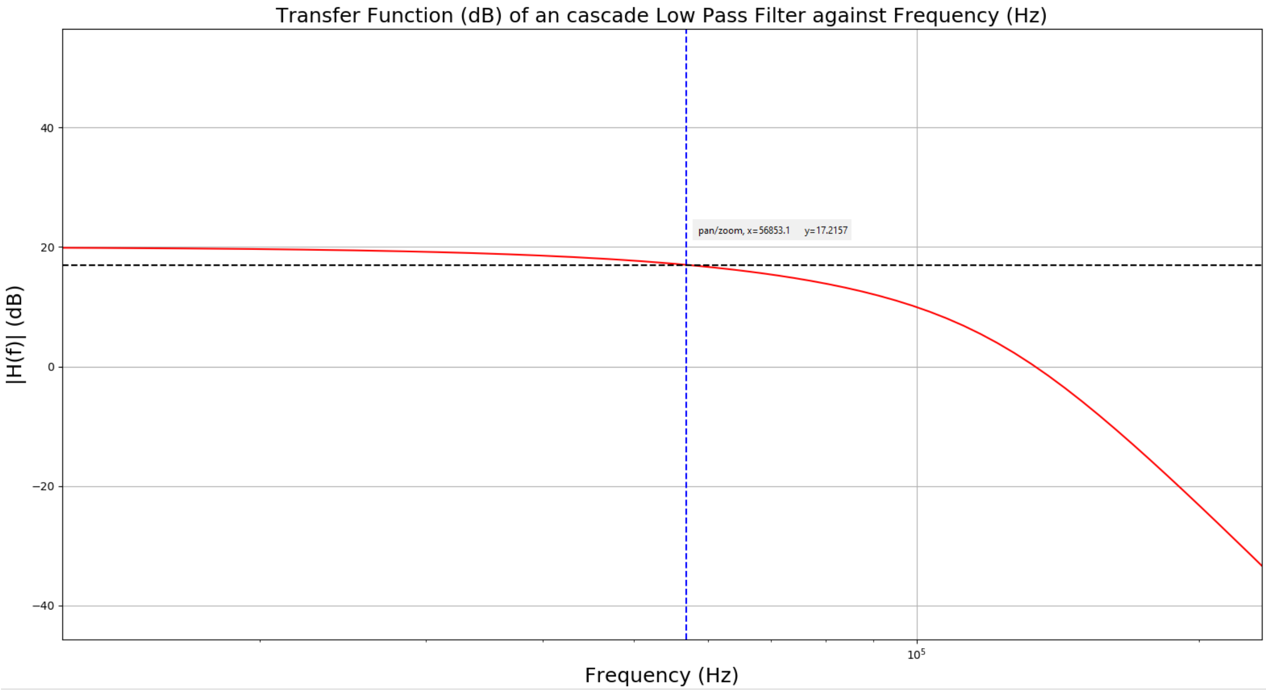

Figure 11: Cascade cut-off and design frequency

4.3 Comparison of transfer functions

4.3.1 Amplitude response

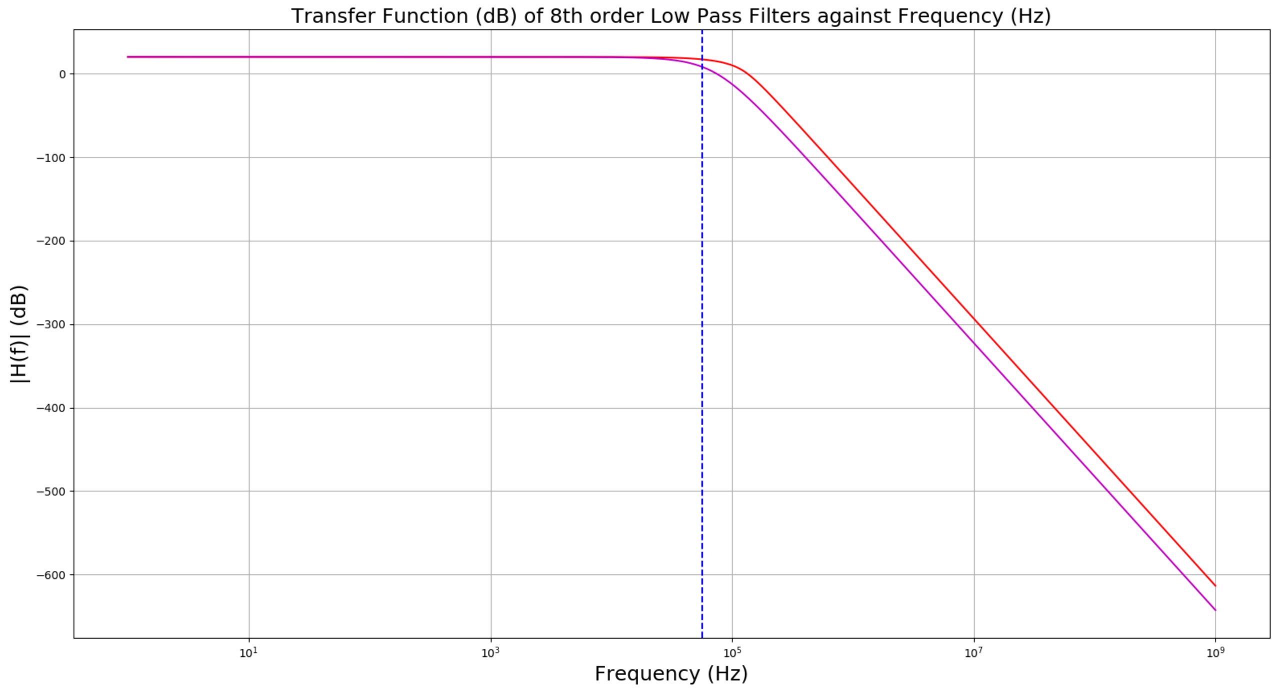

Figure 12: Comparison of amplitude responses, purple is CP, red is Cas

4.3.2 Unity frequency

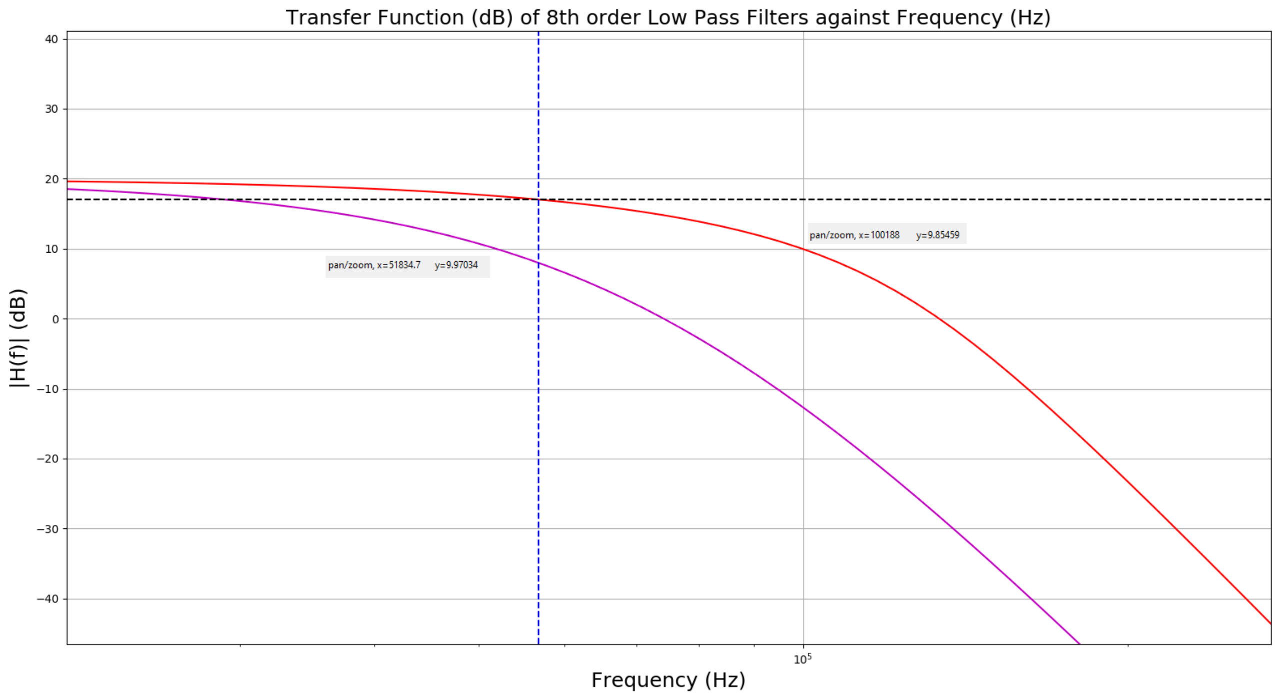

Figure 13: Comparison of unity frequencies, purple is CP, red is Cas

4.3.3 Phase comparison

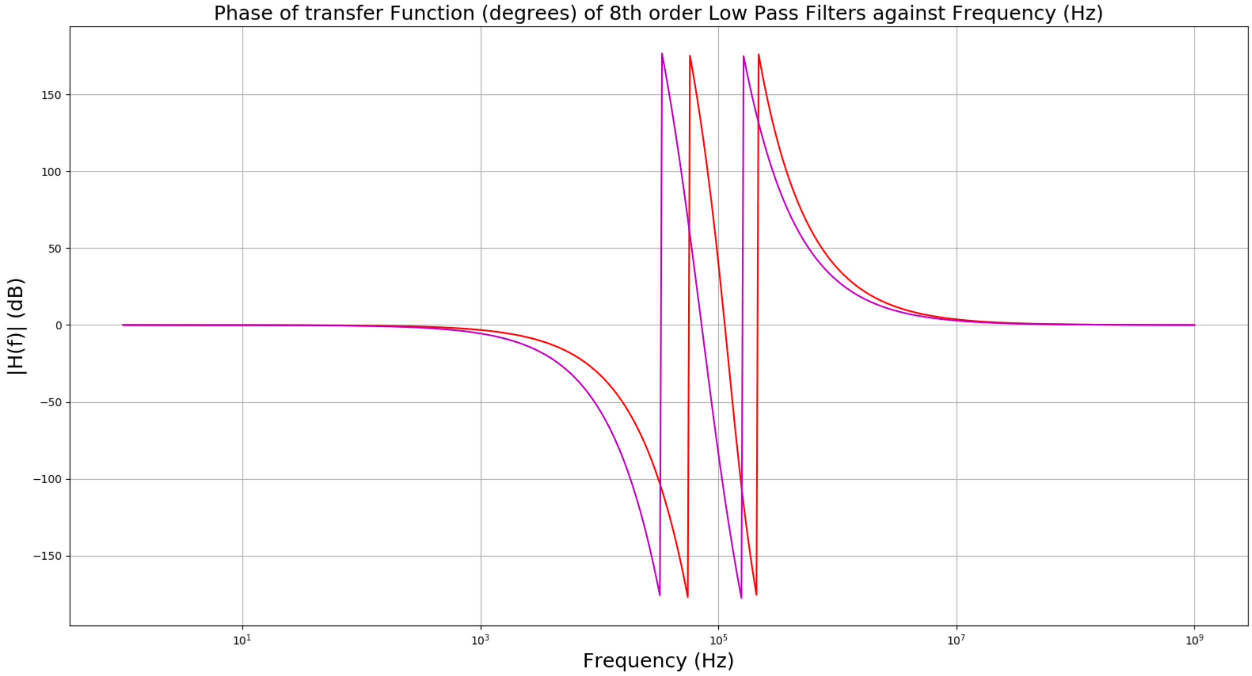

Figure 14: Comparison of phase, purple is CP, red is Cas

4.4 Ideal circuit

4.5 Copy and paste Bessel multi-feedback low-pass filter

4.5.1 Frequency response

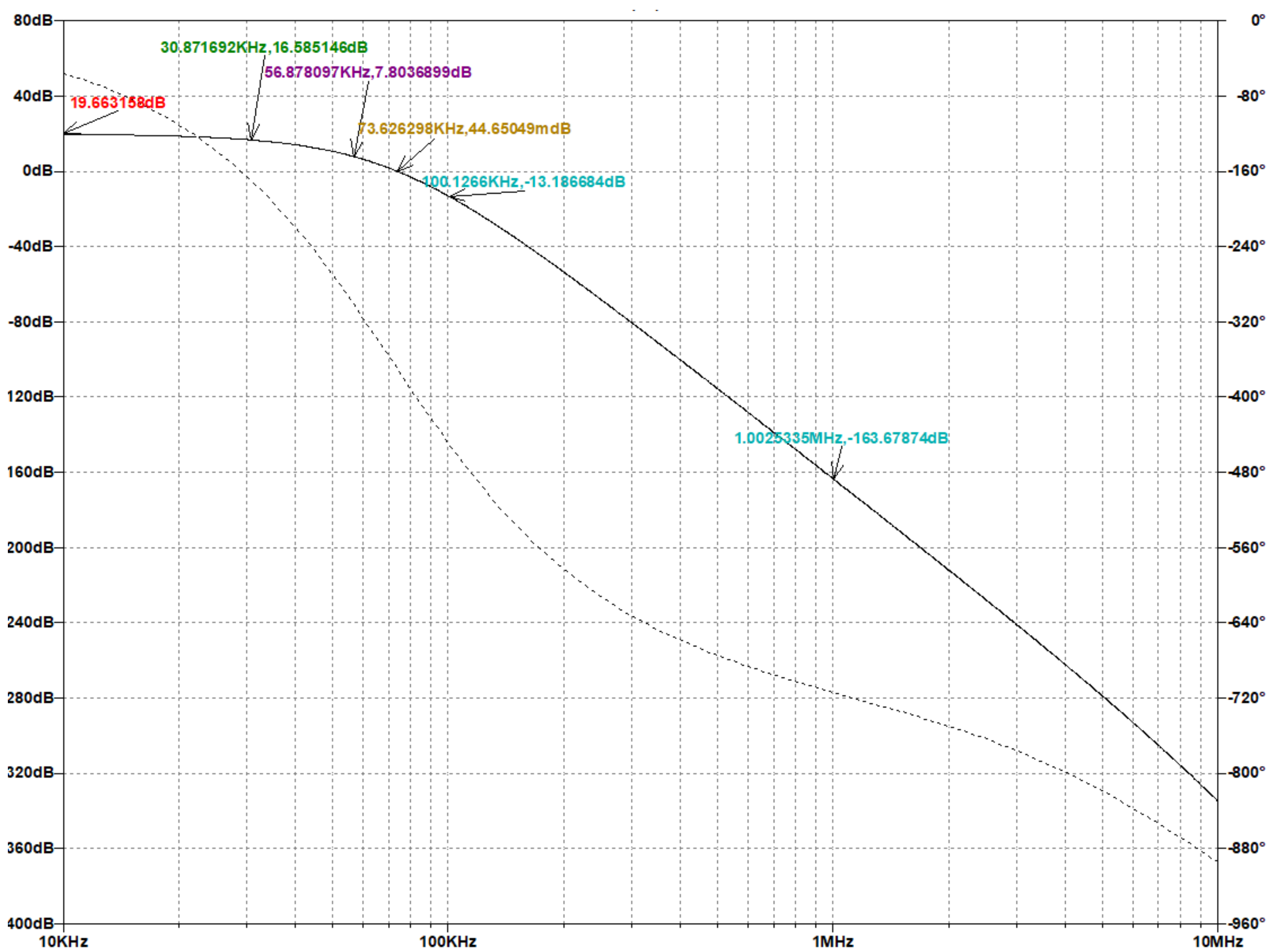

Figure 15: Frequency response

4.5.2 Transient response

Gain response

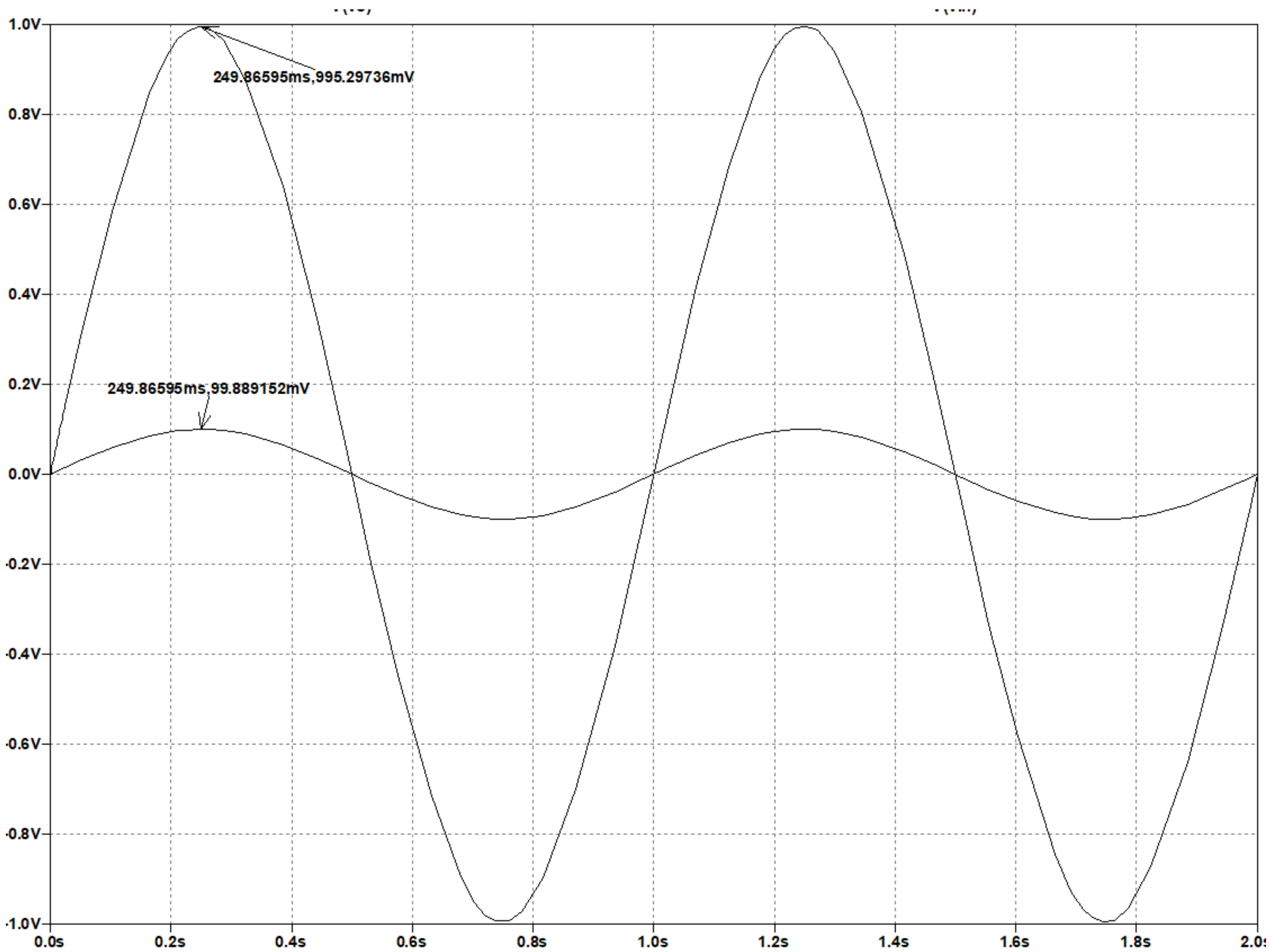

Figure 16: Transient response of voltage gain

Cut-off frequency transient response

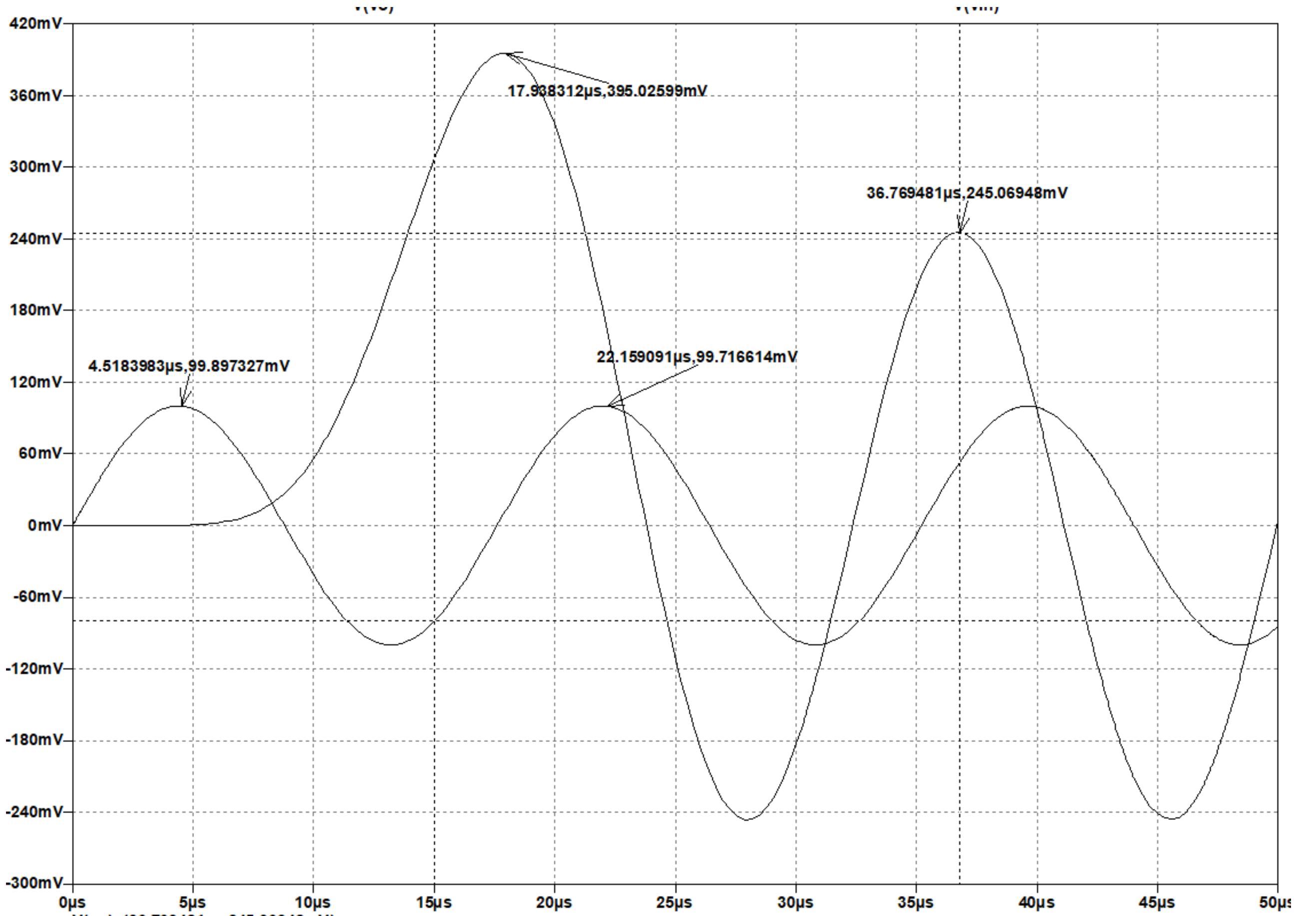

Figure 17: Transient response of phase and gain at cut-off frequency

4.5.3 Some calculations methods

Gain:

$$G = 20 * Log_{10}(|H(j\omega_0)|) \tag{9}$$

Phase difference:

$$Phase = \frac{Time_A - Time_B}{Period} * 360^\circ \tag{10}$$

Final Q:

$$Q = \frac{|H(j\omega_0)|}{|H(j0)|} \tag{11}$$

Where ω_0 is the freq where the phase is 90° relative to the input

4.5.4 Interpretation of results for ideal copy-paste filter

Gain The gain was found to be approximately between 9.5 to 9.9V/V as observed from the gain response and frequency response (red). The gain was found to shift from 395mV to 245mV around the design frequency.

Roll-off: The roll-off was found to be less than the ideal 160dB per decade roll off with 150.5dB per decade roll-off (blue).

Cut-off: The cut off frequency was found to be 30.87KHz (Green).

Design frequency and natural frequency: The design frequency was found to be at 7.8dB which is 8.2dB (46% error) off from the cut off frequency and the natural frequency (ω_0) was found to 16.18KHz from the ninety degree phase shift.

Final Q factor: The overall Q was then found to be 1.0469

Unity frequency: Unity frequency is found to be 73.63KHz.

Phase shift: The phase shift at the design frequency from transient analysis found the phase to 86.14 degrees.

4.6 Cascaded Bessel multi-feedback low-pass filter

4.6.1 Frequency response

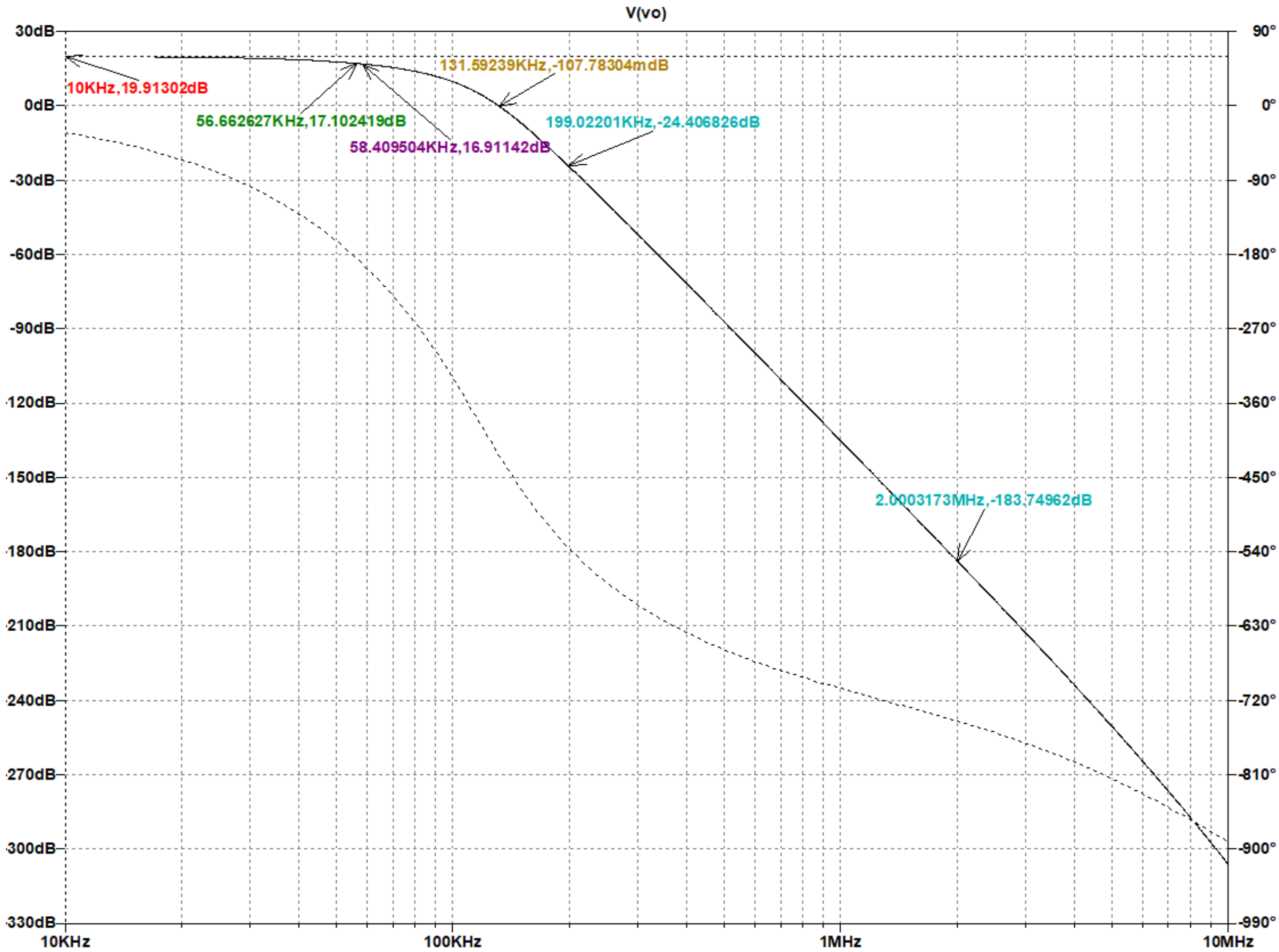

Figure 18: Frequency response

4.6.2 Transient response

Gain response

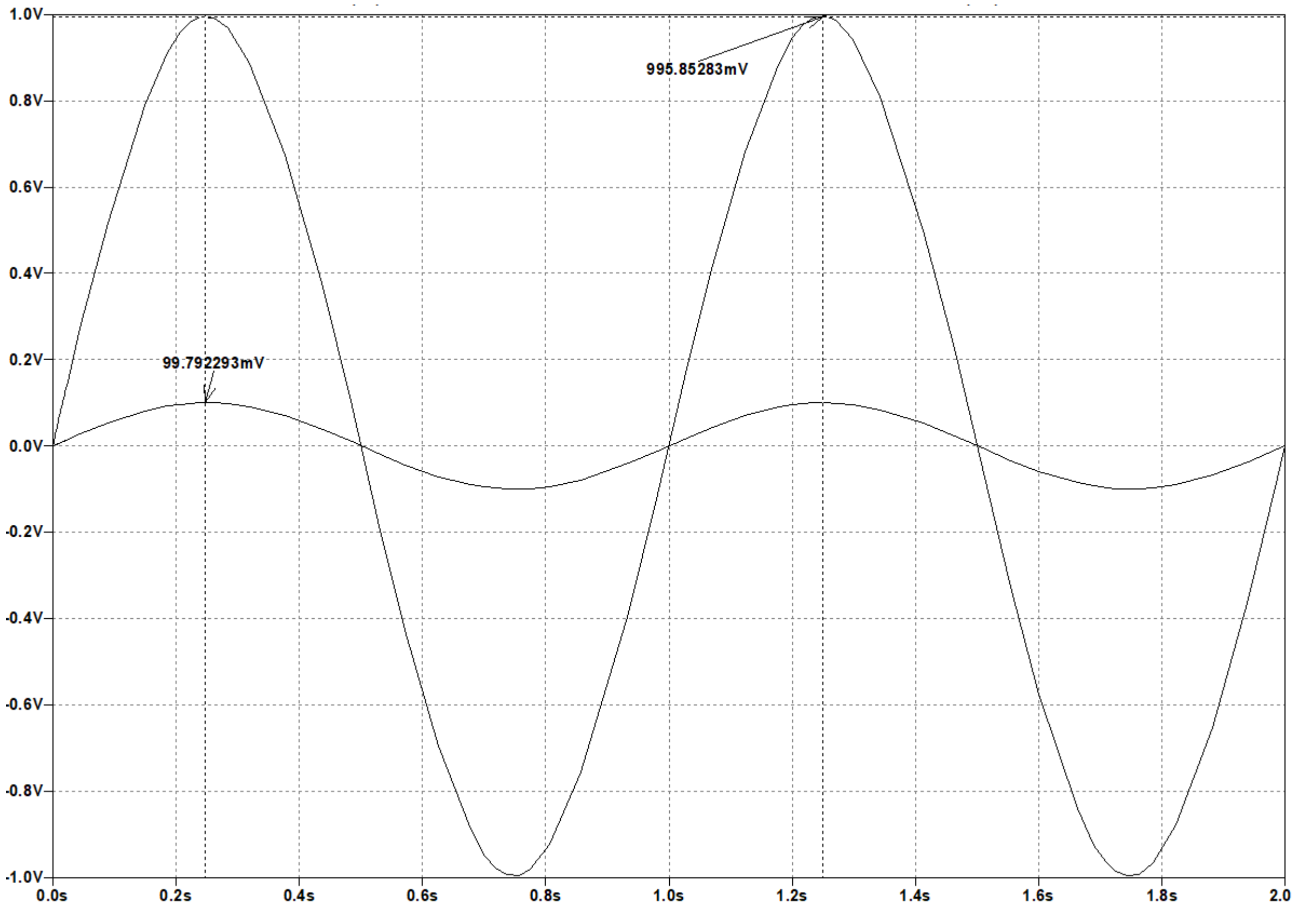

Figure 19: Transient response of voltage gain

Cut-off frequency transient response

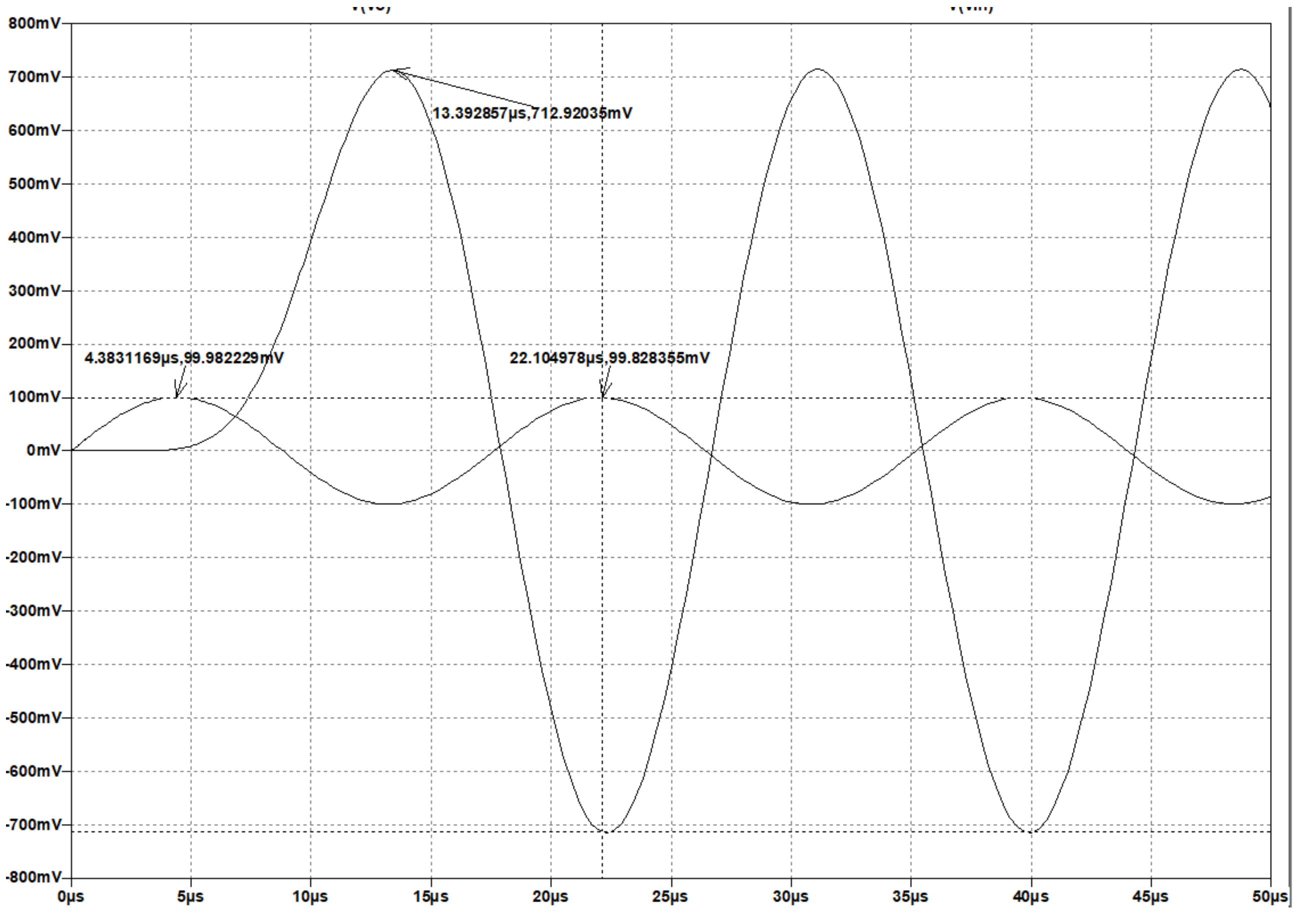

Figure 20: Transient response of phase and gain at cut-off frequency

4.6.3 Interpretation of results for ideal cascaded filter

Gain Gain was found to be 9.9V when compared with the transient and frequency response (Red).

Roll-off Roll off was found to be close to ideal at 159.34dB per decade (Blue).

Cut-off The cut off was found to be at 58KHz (Green).

Design frequency and natural frequency The design frequency had a magnitude of approximately 17.1dB (1% error). The natural frequency was to be 27.5KHz when measured from the ninety degree phase shift.

Final Q factor The final Q factor was found to be 0.97

Unity frequency The unity gain frequency was found to e 131.59KHz

Phase shift The phase shift was found to be 151.33 degrees from the cut-off (design) frequency transient response

4.7 E6/E12 circuit

4.8 Copy and paste Bessel multi-feedback low-pass filter

4.8.1 Frequency response

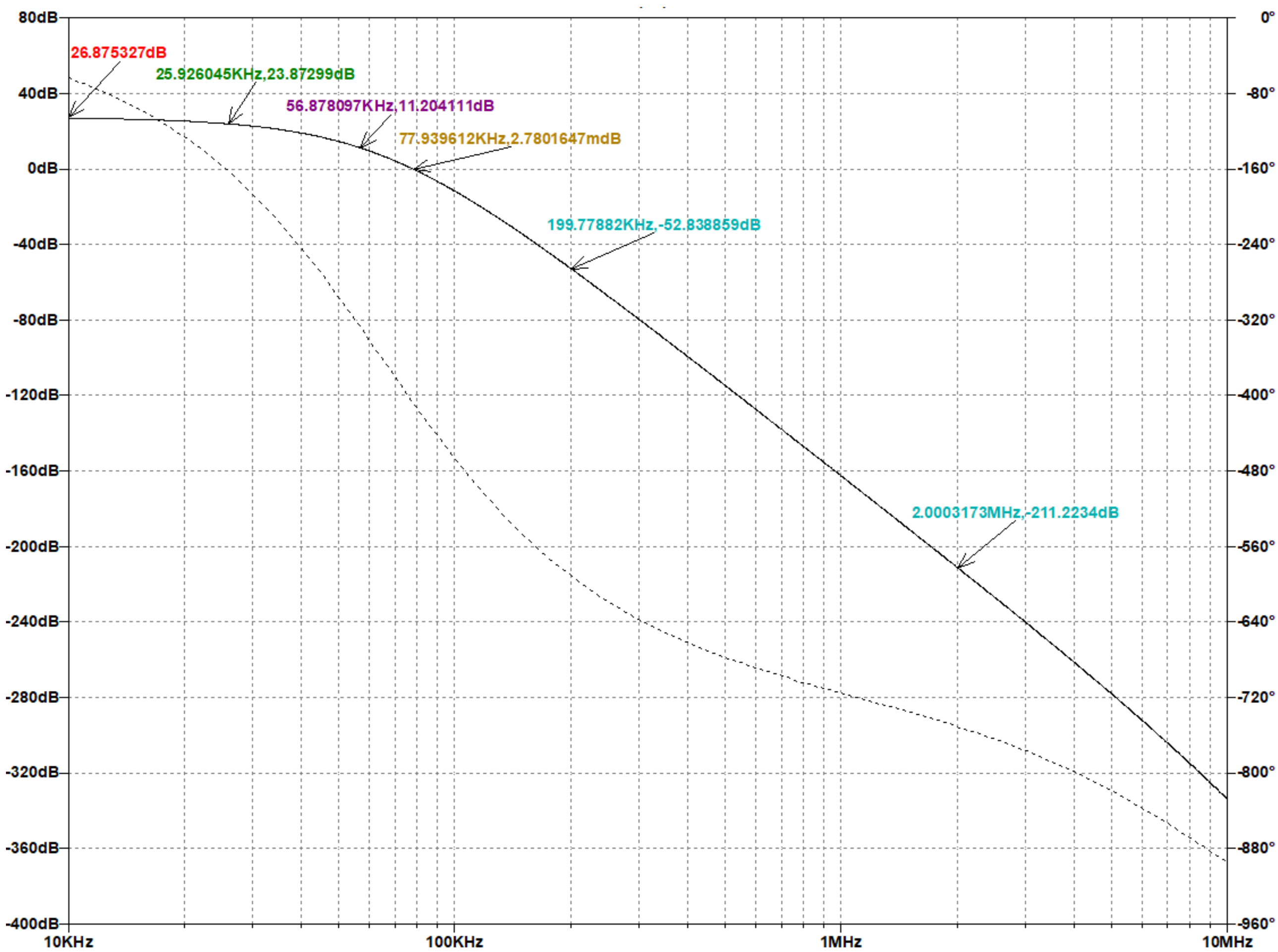

Figure 21: Frequency response

4.8.2 Transient response

Gain response

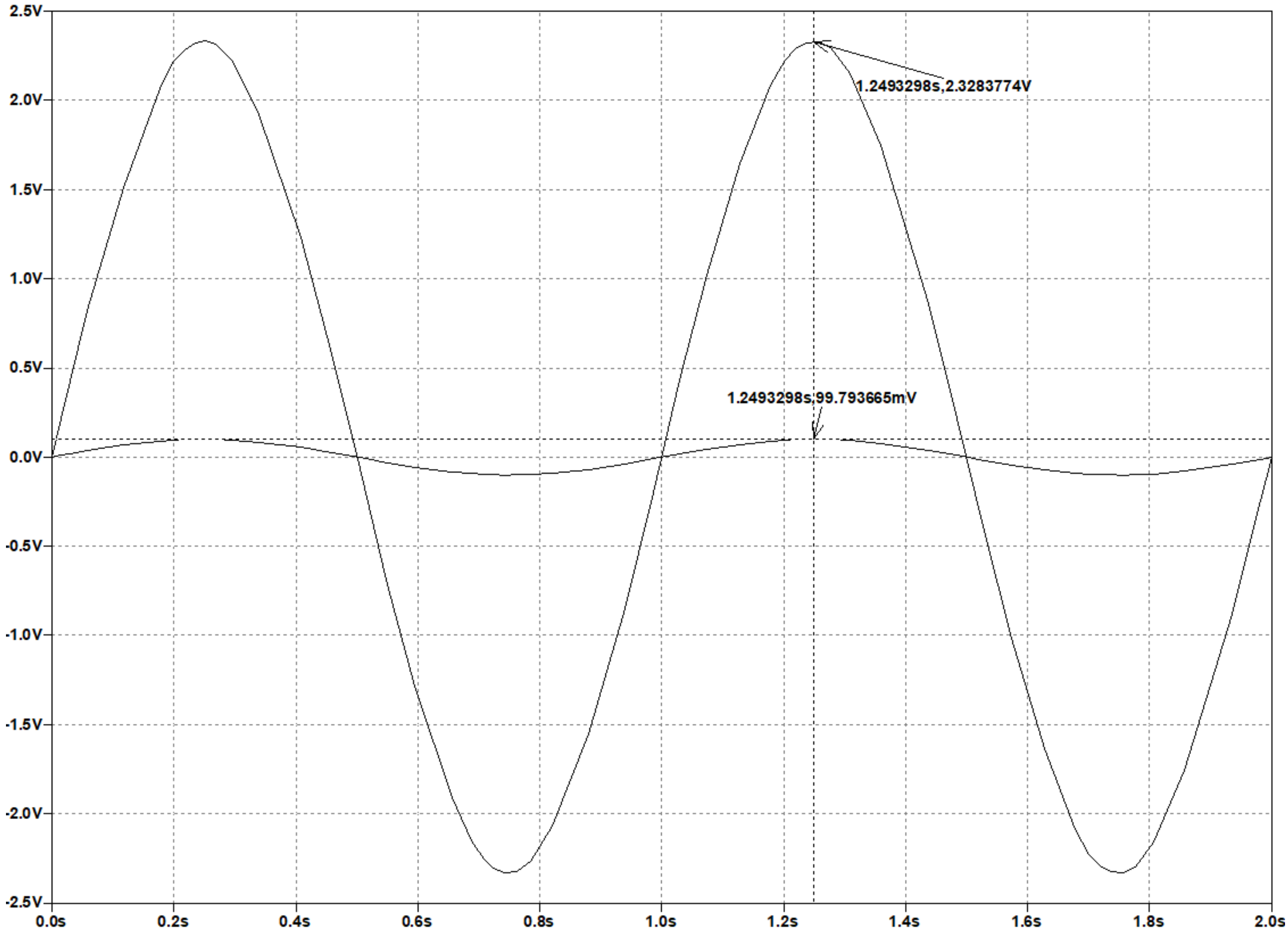

Figure 22: Transient response of voltage gain

Cut-off frequency transient response

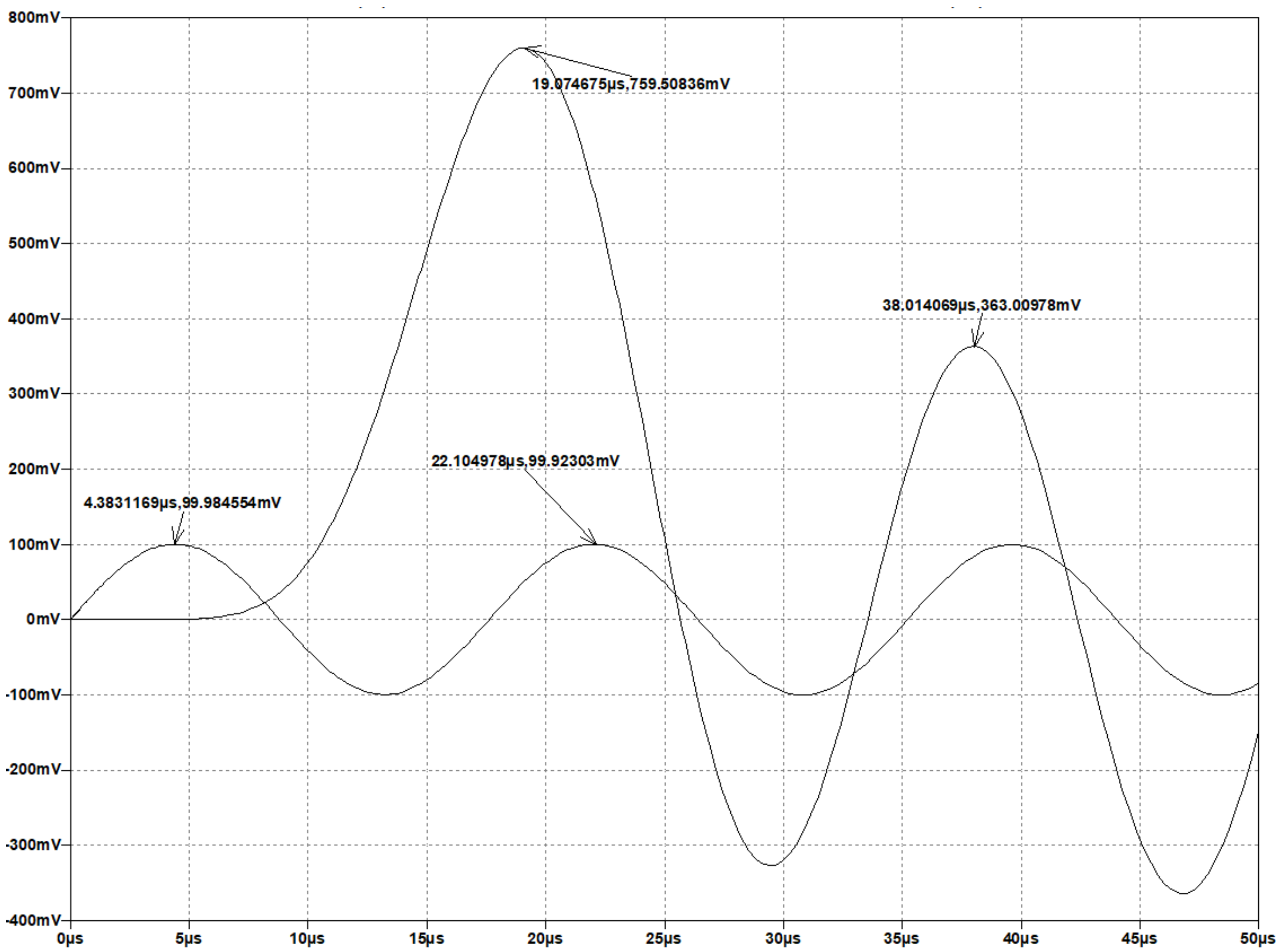

Figure 23: Transient response of phase and gain at cut-off frequency

4.8.3 Interpretation of results for E6/E12 copy-paste filter

Gain Gain was found to be 22V/V when compared with the transient and frequency response (Red).

Roll-off Roll off was found to be close to ideal at 158.4dB per decade (Blue).

Cut-off The cut off was found to be at 25.93KHz (Green).

Design frequency and natural frequency The design frequency had a magnitude of approximately 11.2dB (53% error). The natural frequency was to be 26.4KHz when measured from the ninety degree phase shift.

Final Q factor The final Q factor was found to be 0.98

Unity frequency The unity gain frequency was found to be 77.94KHz

Phase shift The phase shift was fund to be 61.35 degrees from the cut-off (design) frequency transient response

4.9 Cascaded Bessel multi-feedback low-pass filter

4.9.1 Frequency response

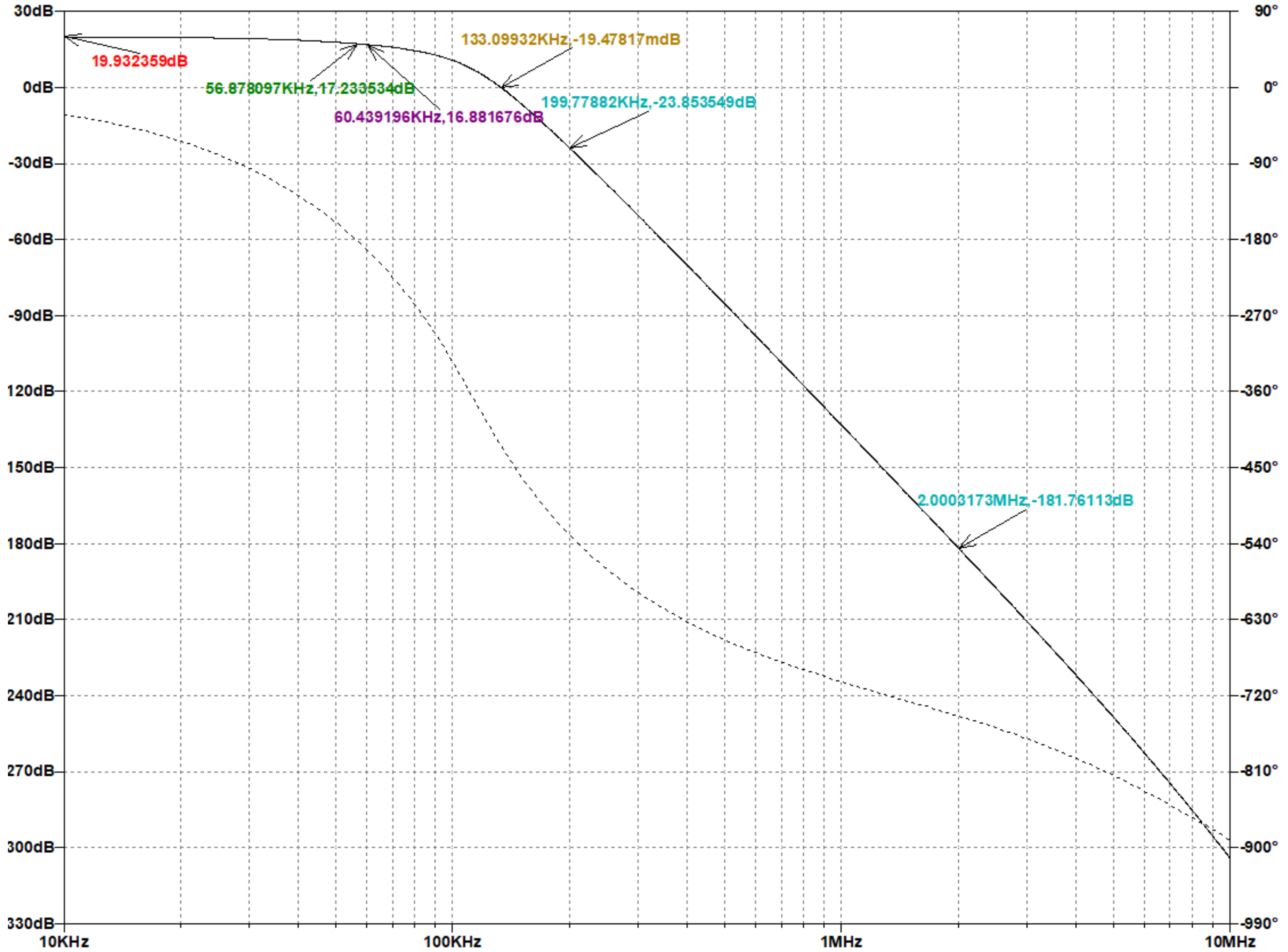

Figure 24: Frequency response

4.9.2 Transient response

Gain response

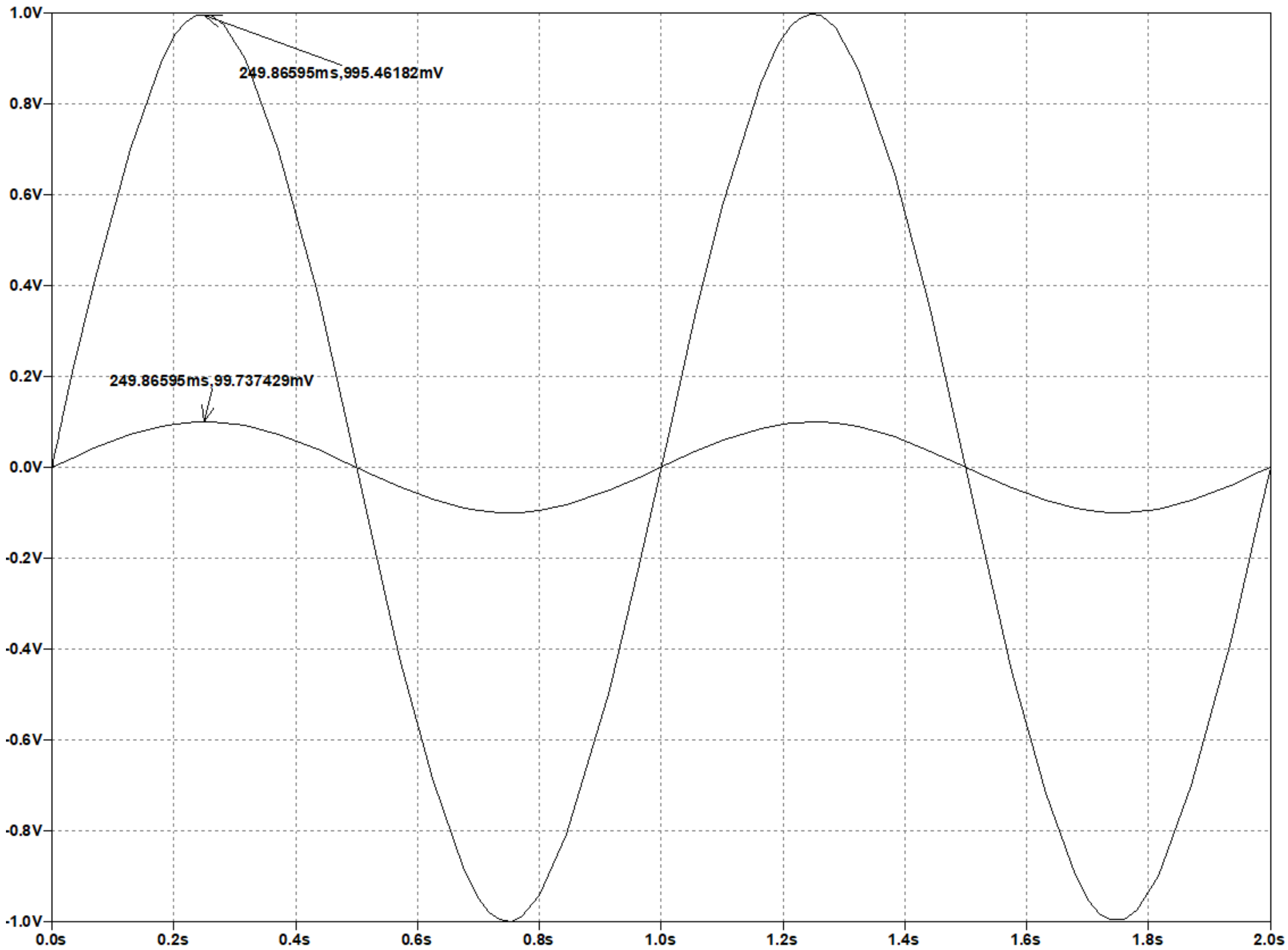

Figure 25: Transient response of voltage gain

Cut-off frequency transient response

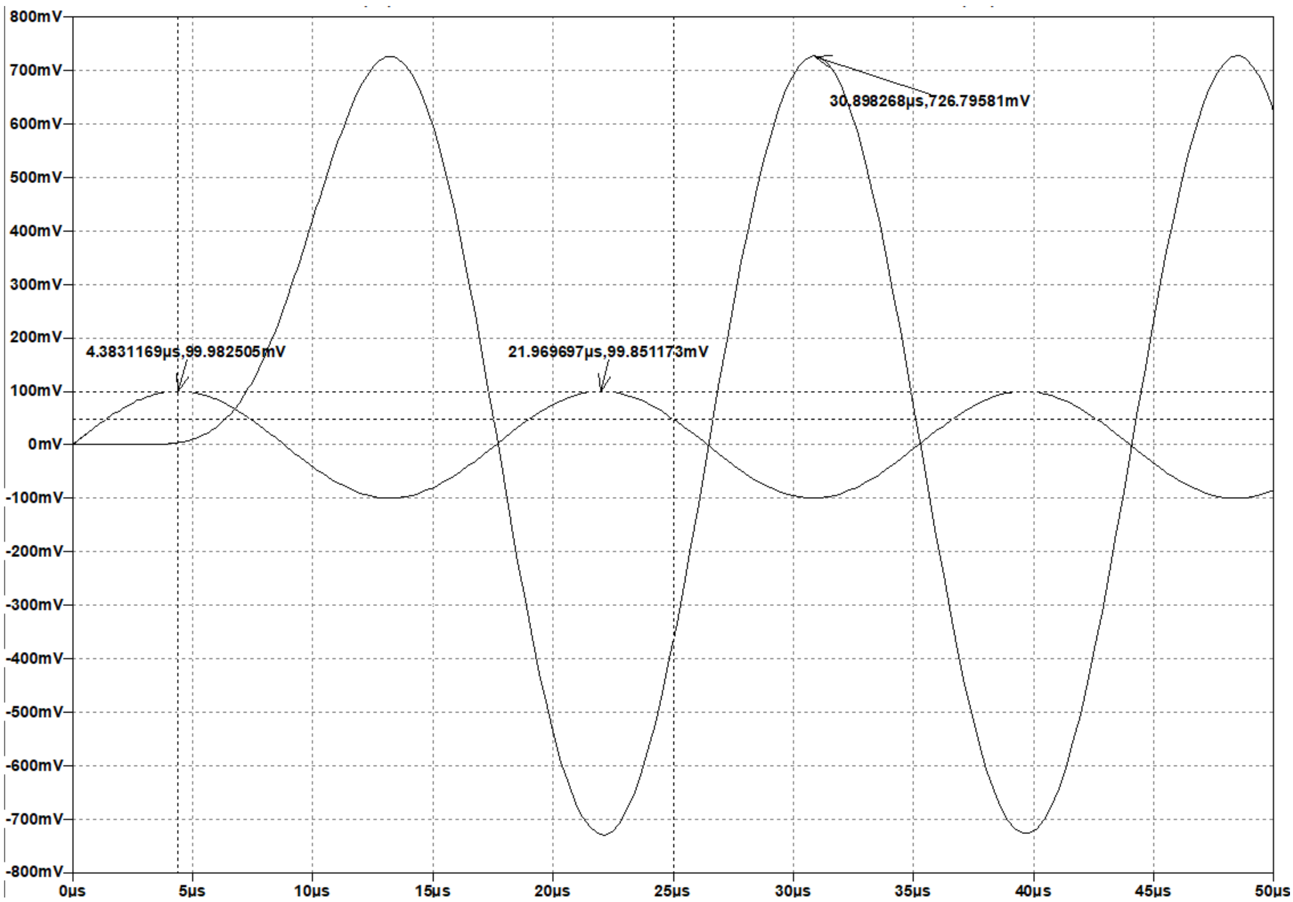

Figure 26: Transient response of phase and gain at cut-off frequency

4.10 Monte Carlo

Monte carlo analysis of the cascaded circuit for further observations

4.10.1 Frequency response

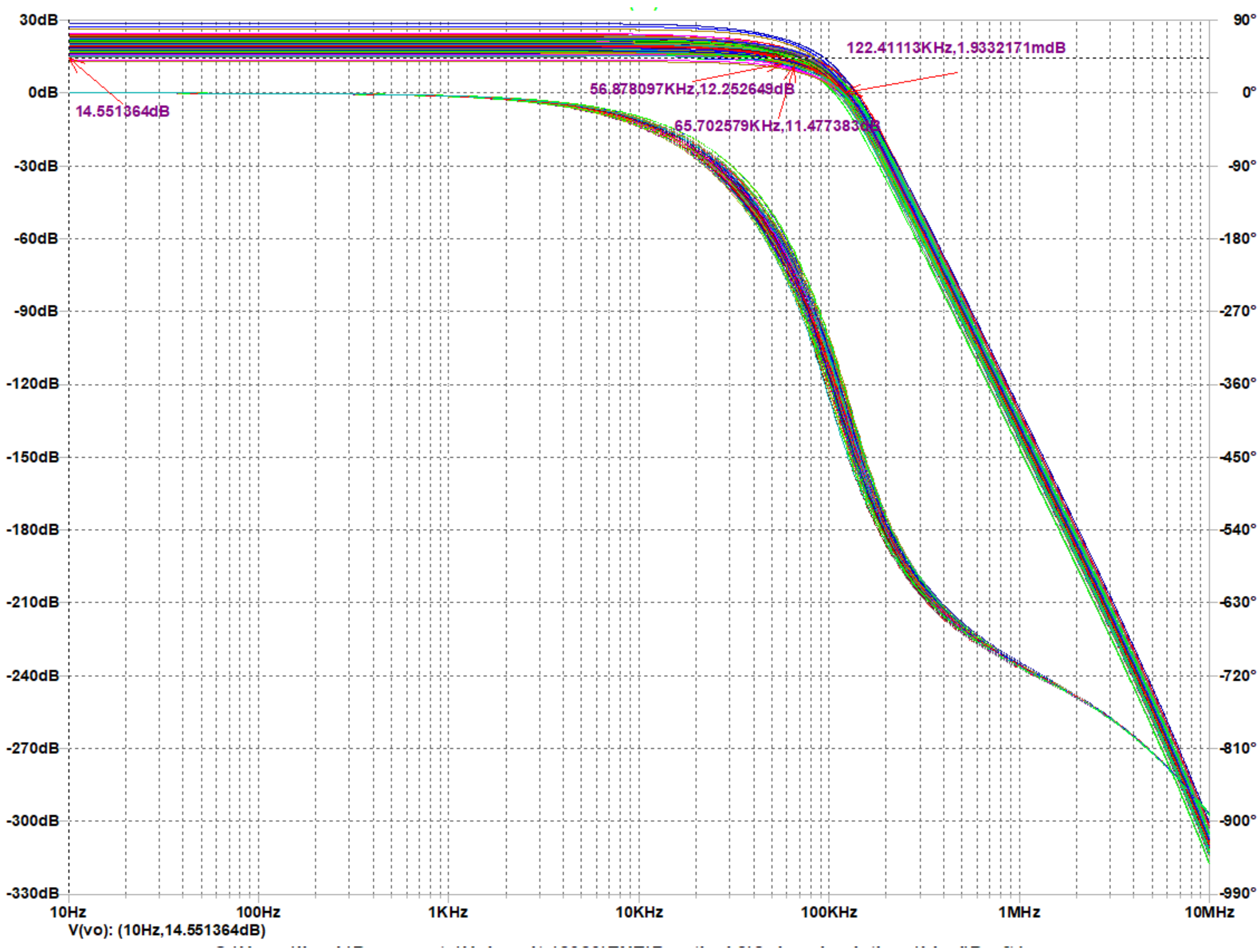

Figure 27: Monte Carlo analysis of Frequency response

4.10.2 Amplitude response

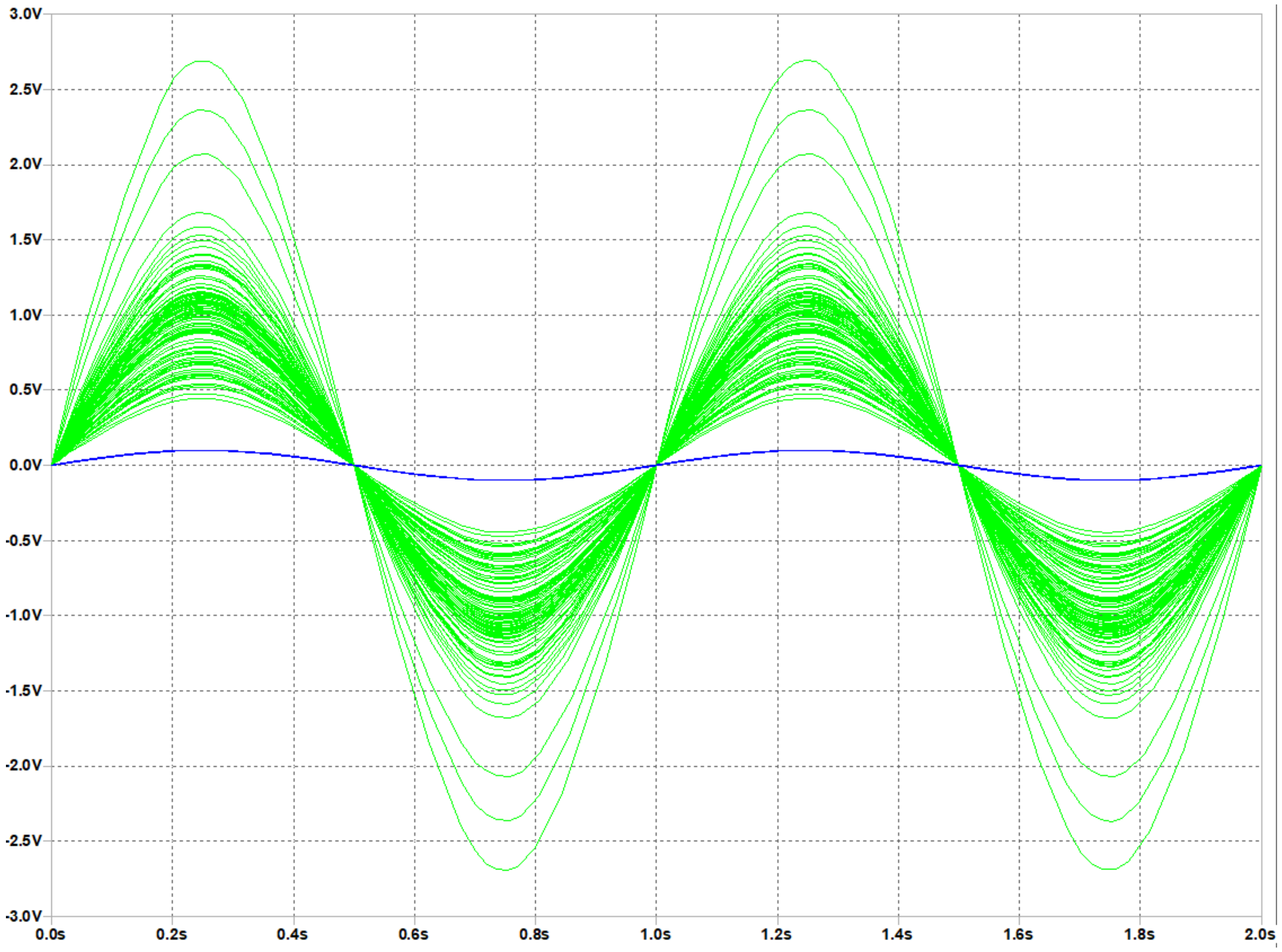

Figure 28: Monte Carlo analysis of Amplitude response

4.10.3 Cut off amplitude response

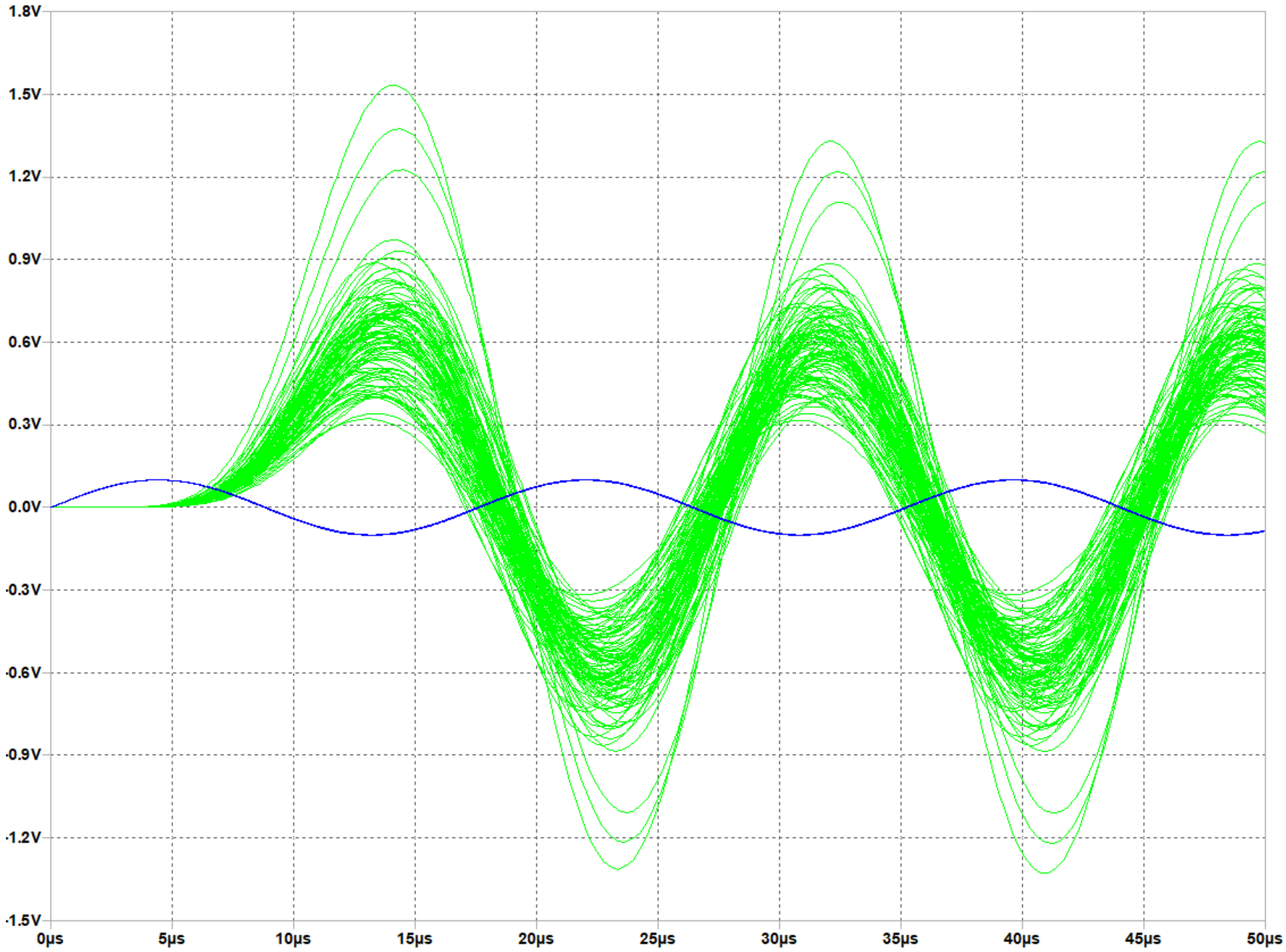

Figure 29: Monte Carlo analysis of Cut off amplitude response

4.10.4 Interpretation of results for E6/E12 cascaded filter

Gain Gain was found to be averaging around 9.95V/V when compared with the transient and frequency response (Red) and Monte Carlo analysis indicated a range of 5V/V to 29V/V when the resistors could vary by twenty percent and capacitors by ten percent.

Roll-off Roll off was found to be close to ideal at 158dB per decade (Blue) .

Cut-off The cut off was found to be at 60.44KHz (Green) and Monte Carlo analysis found a range of approximately 58 to 66KHz.

Design frequency and natural frequency The design frequency had a magnitude of approximately 17.2dB (2% error). The natural frequency was to be 28.5KHz when measured from the ninety degree phase shift. Monte Carlo tends to shift the natural frequency by approximately +-10Khz.

Final Q factor The final Q factor was found to be 0.968

Unity frequency The unity gain frequency was found to be 133.1KHz and vary by 10dB higher and lower in Monte Carlo analysis.

Phase shift The phase shift was found to be 182.76 degrees from the cut-off (design) frequency in the transient response

4.11 E96/E24 circuit

E96/E24 components are used in conjunction with the non-ideal op-amp simulations

4.12 Copy and paste Bessel multi-feedback low-pass filter

4.12.1 Frequency response

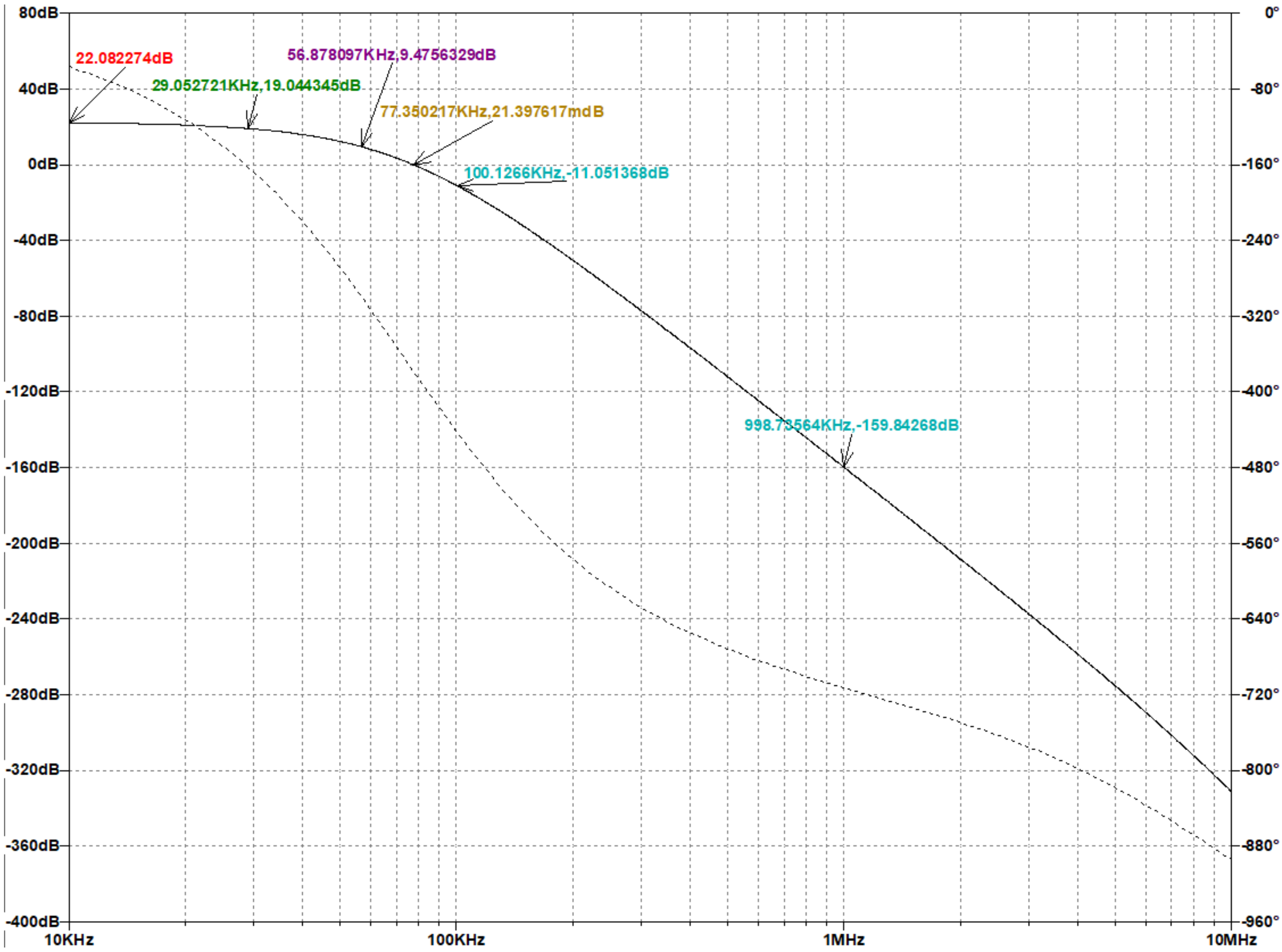

Figure 30: Frequency response

4.12.2 Transient response

Gain response

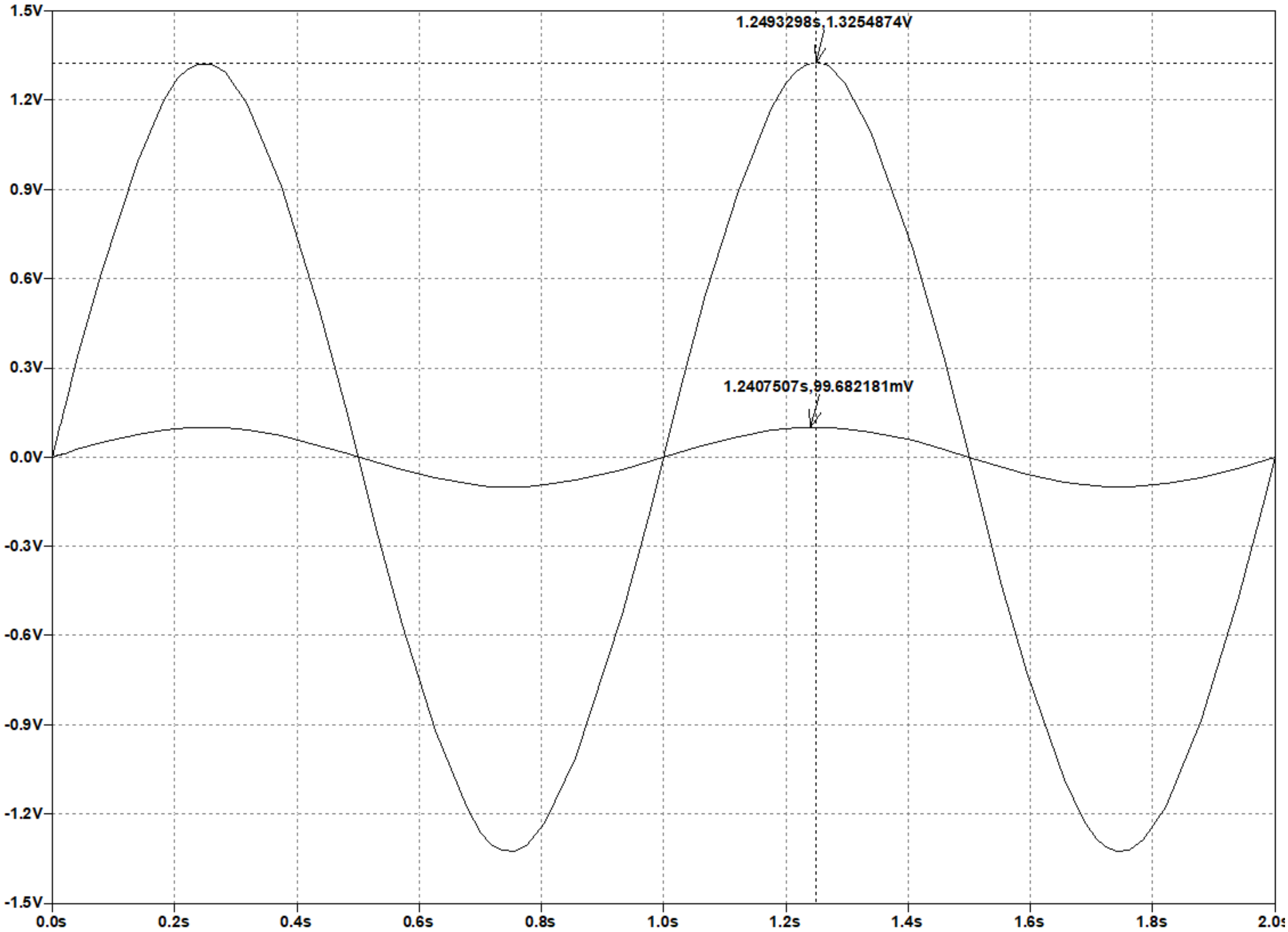

Figure 31: Transient response of voltage gain

Cut-off frequency transient response

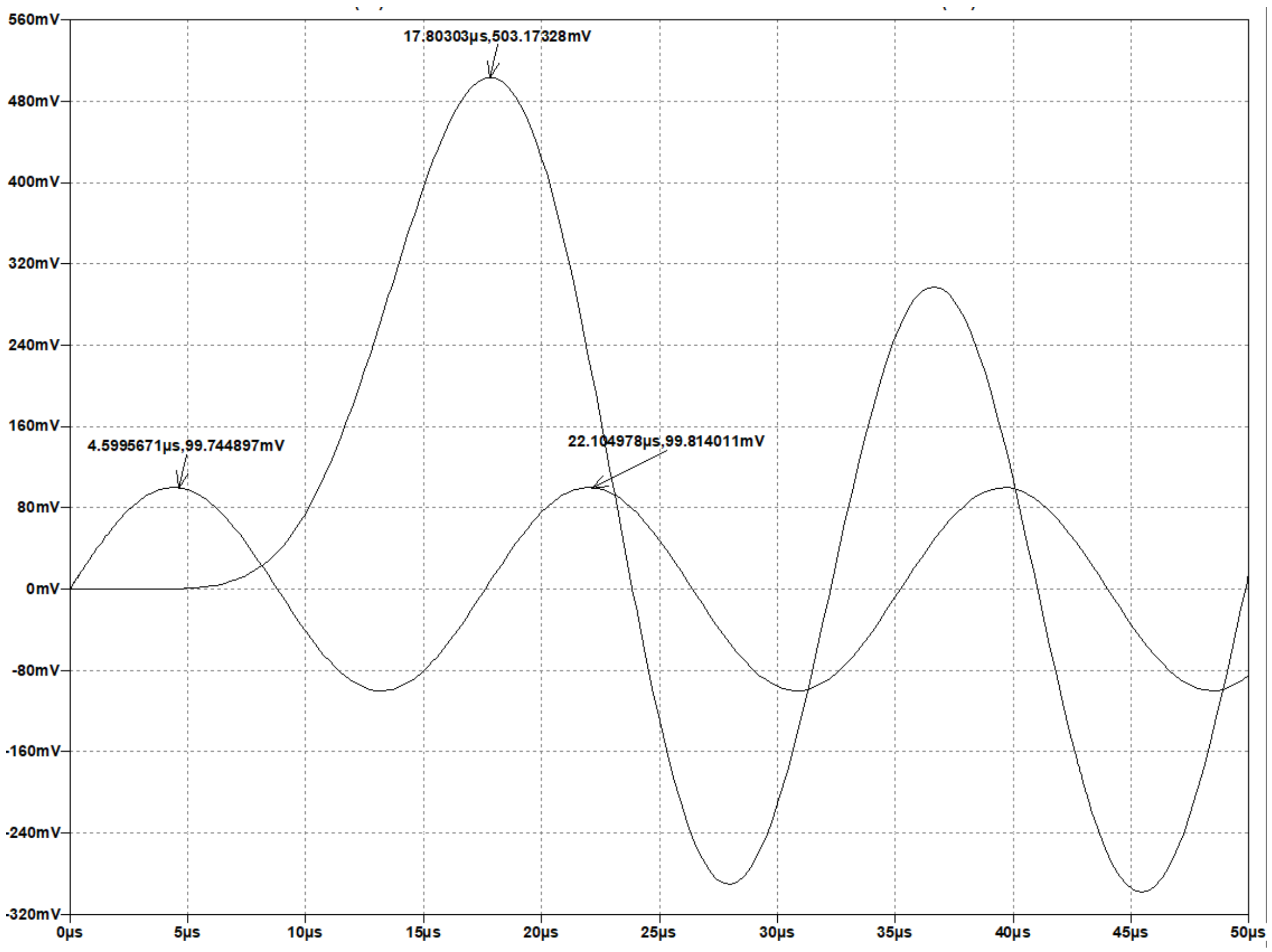

Figure 32: Transient response of phase and gain at cut-off frequency

4.13 Cascaded Bessel multi-feedback low-pass filter

4.13.1 Frequency response

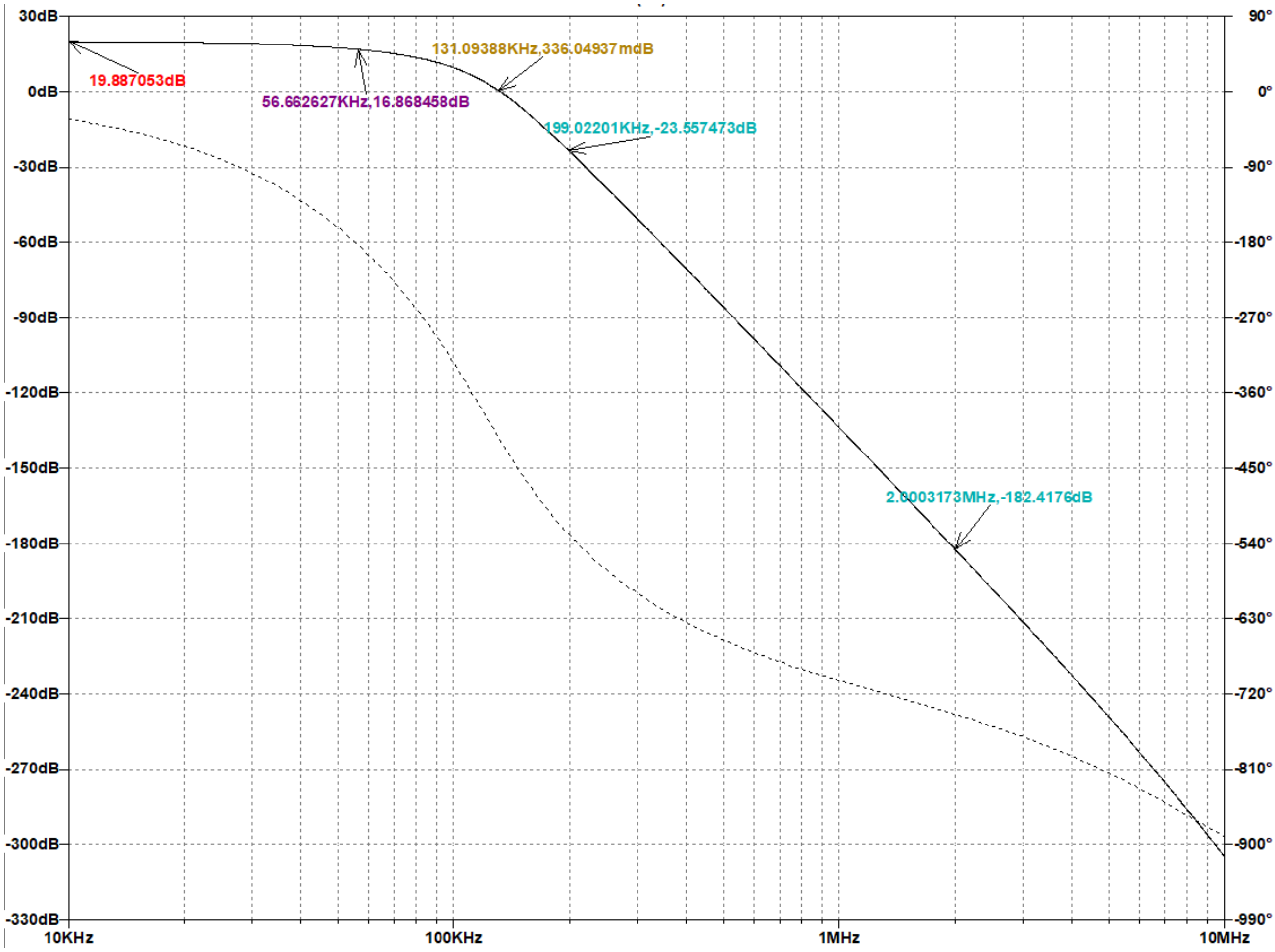

Figure 33: Frequency response

4.13.2 Transient response

Gain response

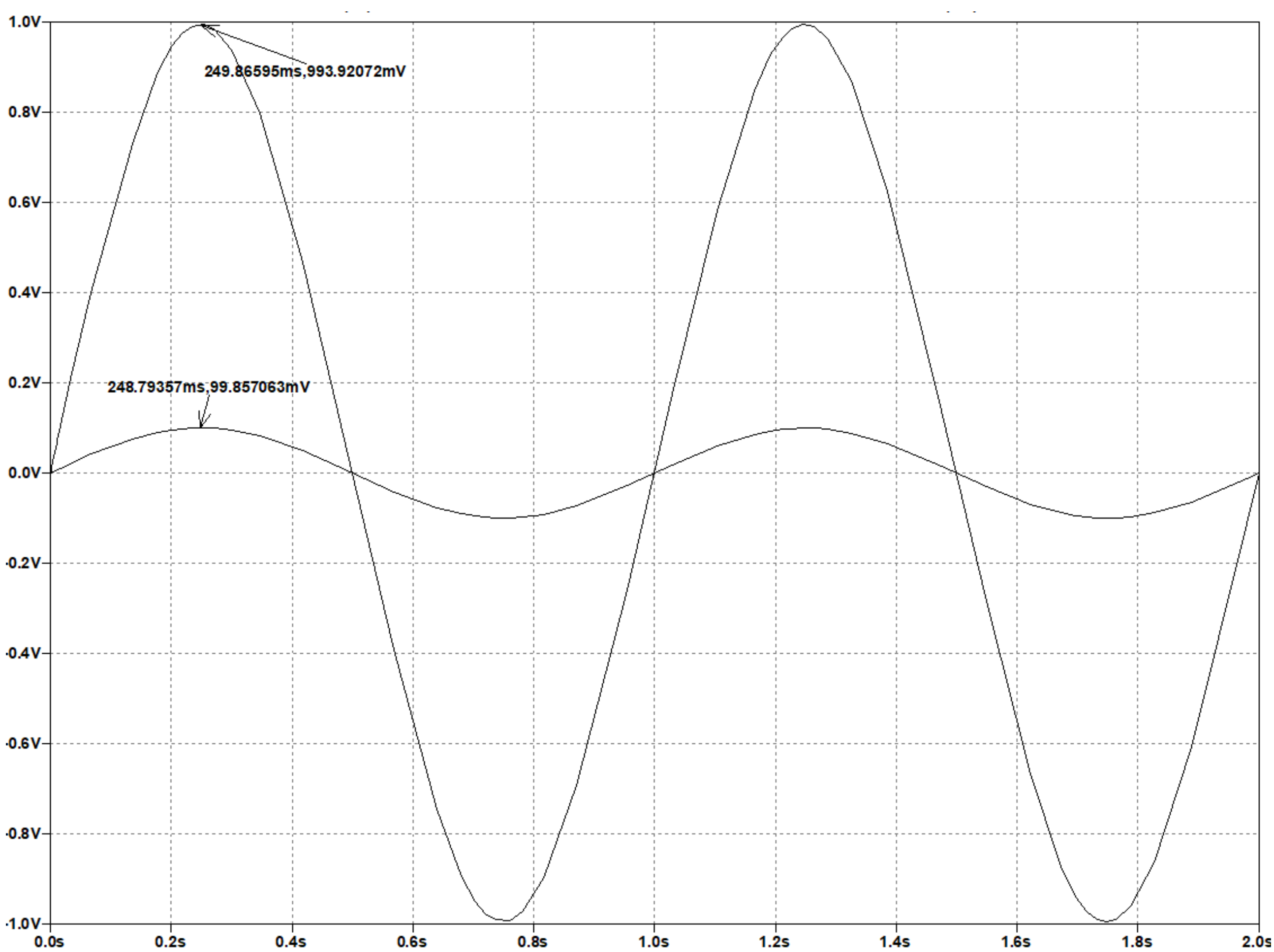

Figure 34: Transient response of voltage gain

Cut-off frequency transient response

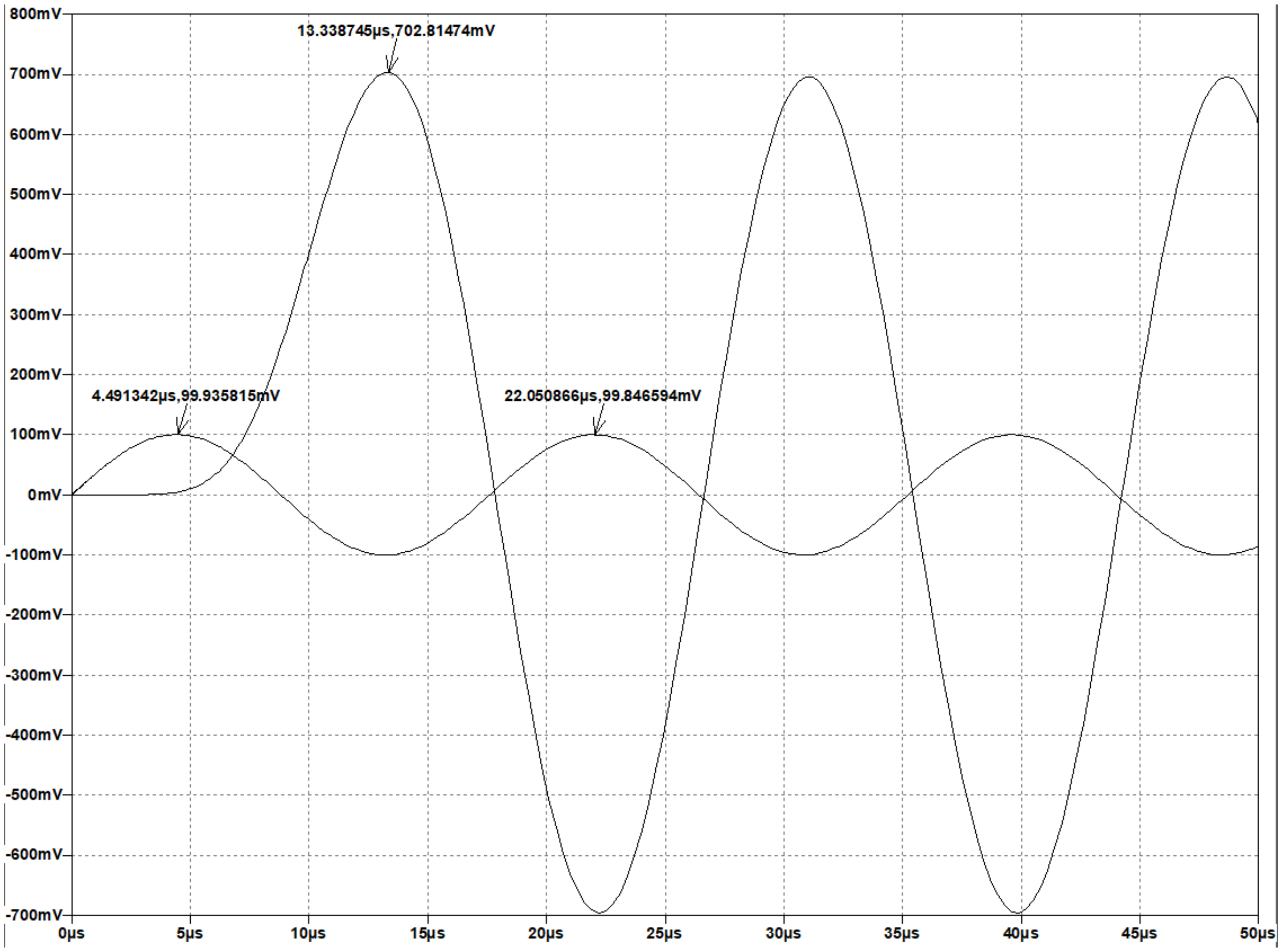

Figure 35: Transient response of phase and gain at cut-off frequency

4.14 Non-ideal components circuit

The circuits are comprised of E96/E24 resistors and capacitors with the op-amp being LF347.

4.15 Copy and paste Bessel multi-feedback low-pass filter

4.15.1 Frequency response of LM347

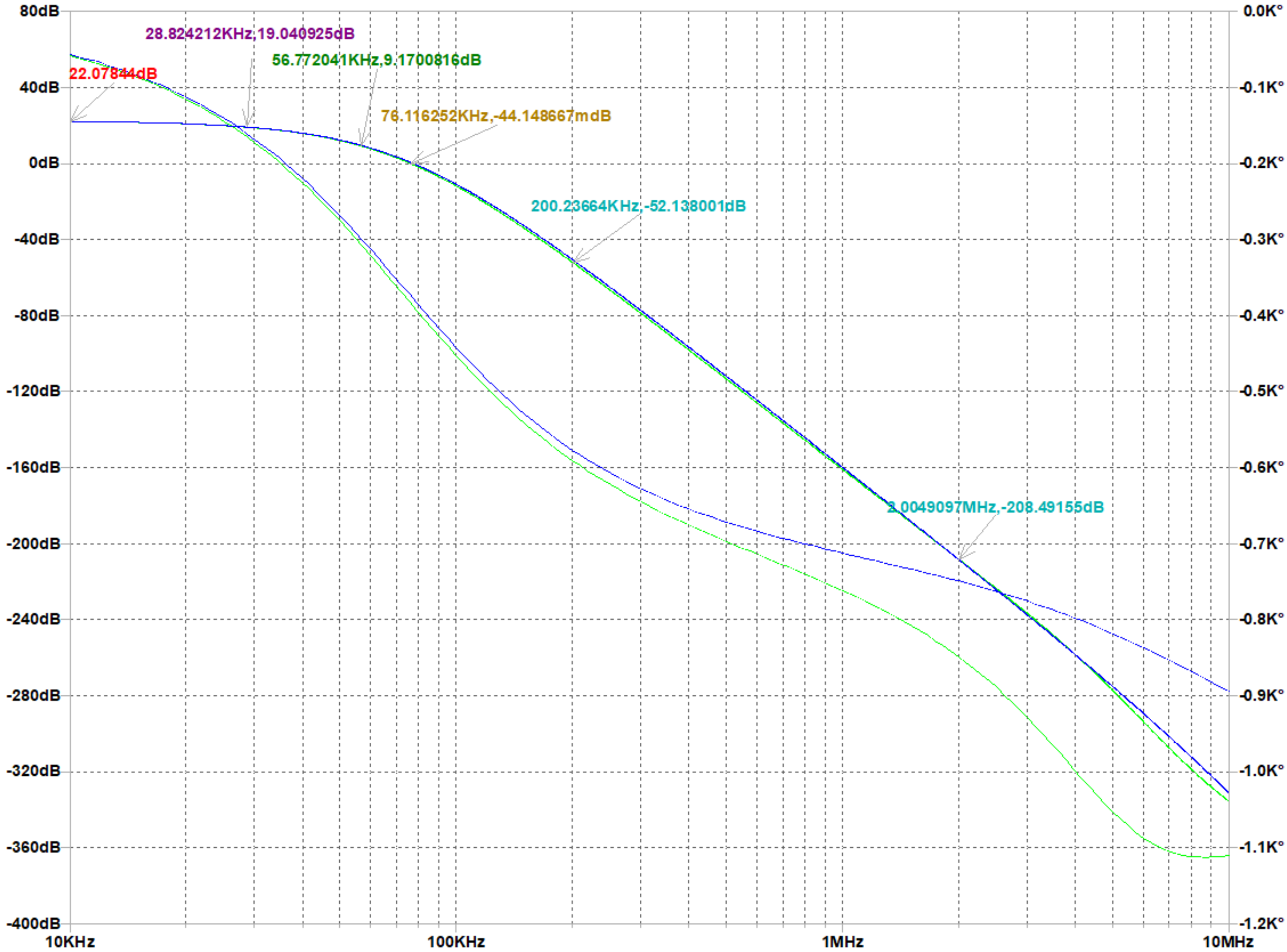

Figure 36: Frequency response

4.15.2 Frequency response of MCP604

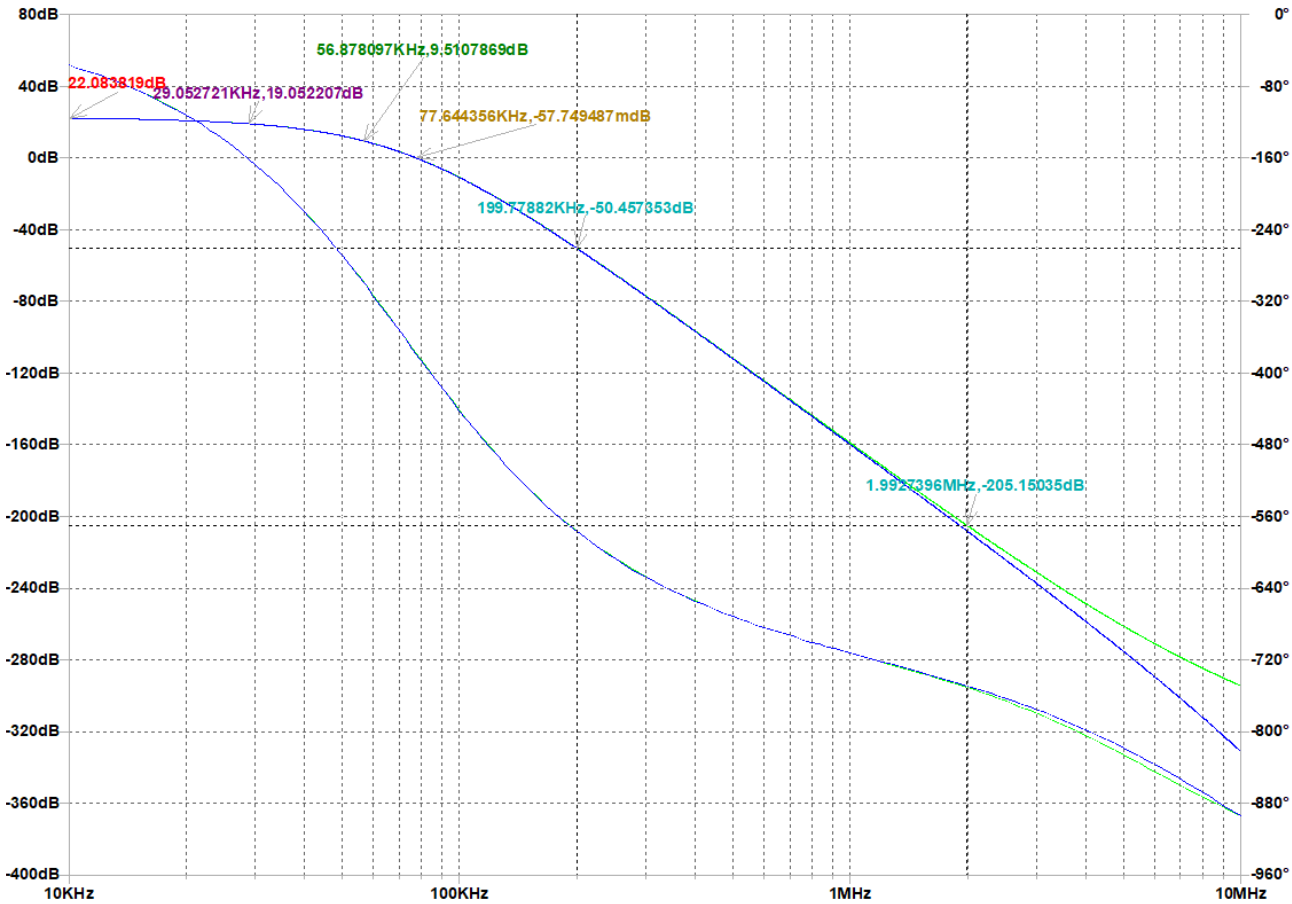

Figure 37: Frequency response

4.15.3 Transient response

Gain response of LM347

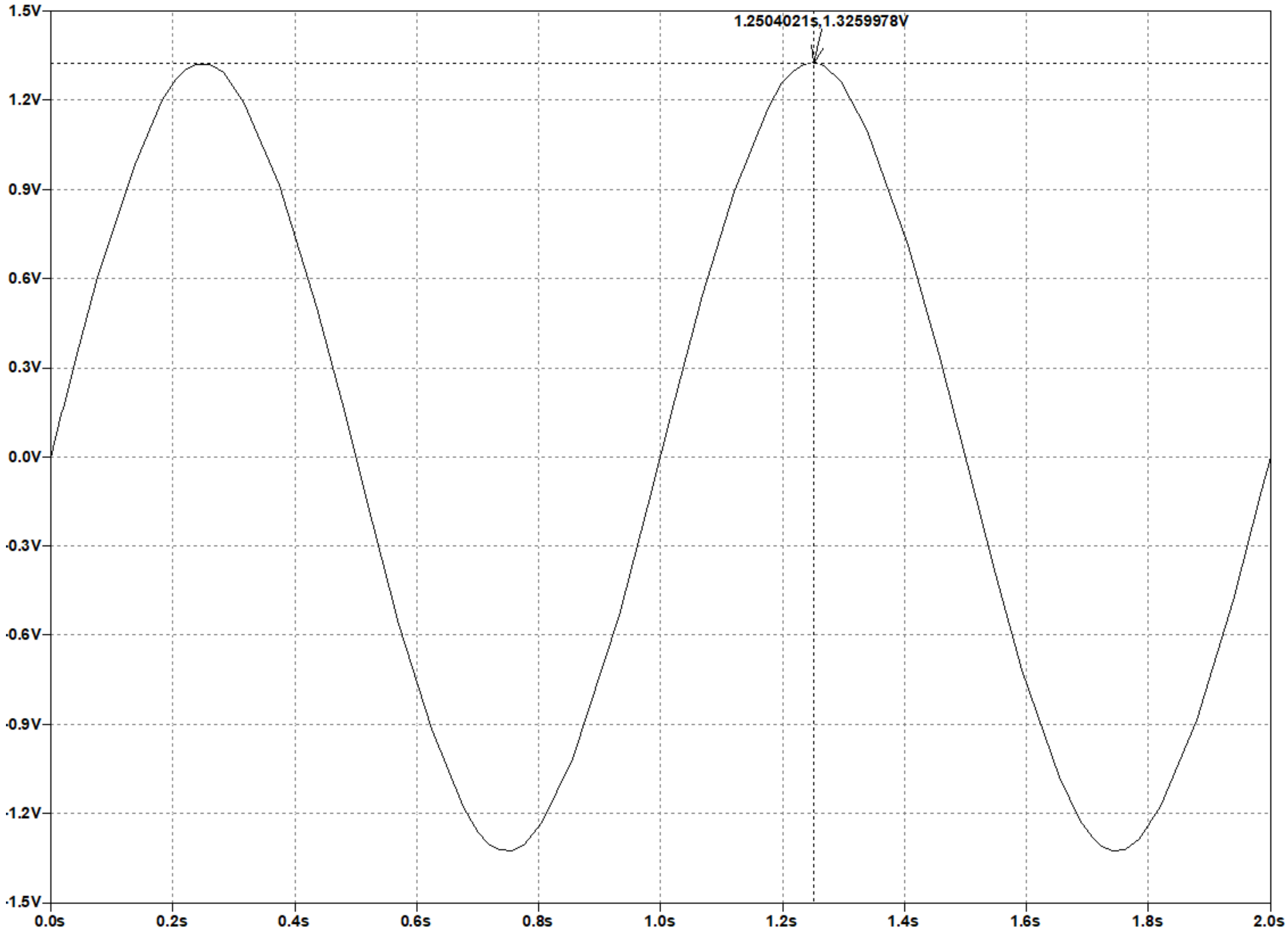

Figure 38: Transient response of voltage gain

Cut-off frequency transient response

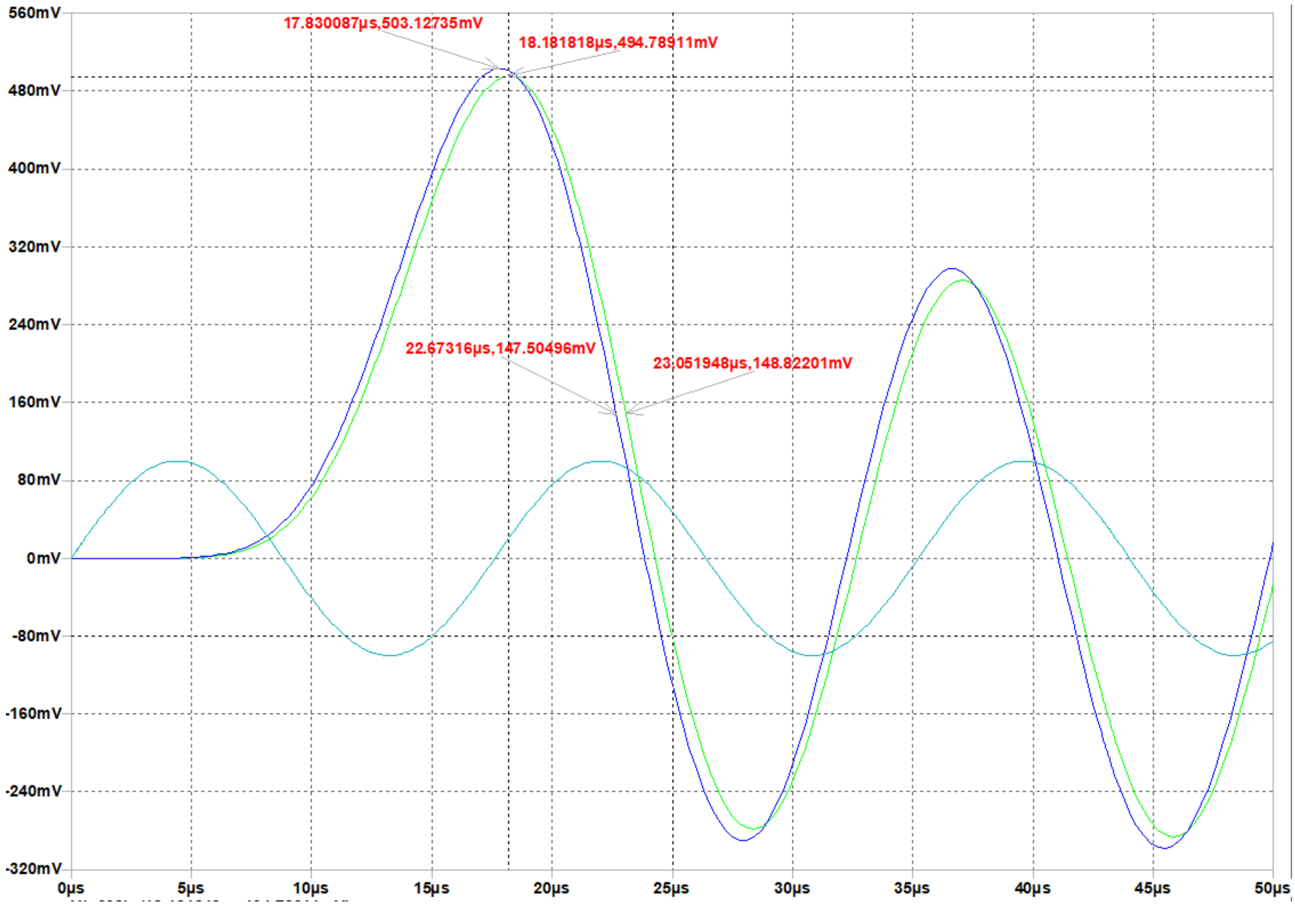

Figure 39: Transient response of phase and gain at cut-off frequency

4.16 Cascaded Bessel multi-feedback low-pass filter

4.16.1 Frequency response vs LF347

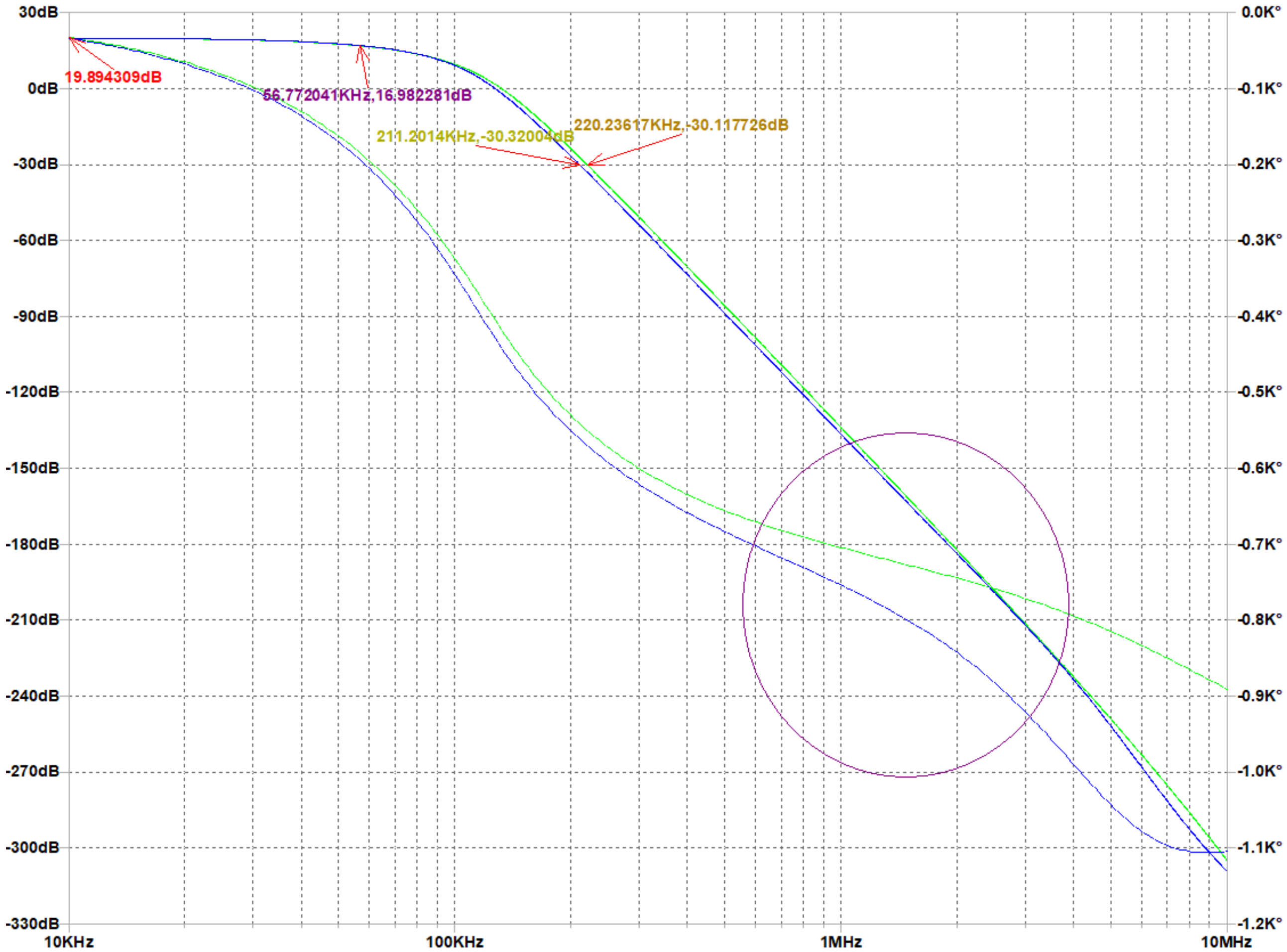

Figure 40: Frequency response

4.16.2 Frequency response vs MCP604

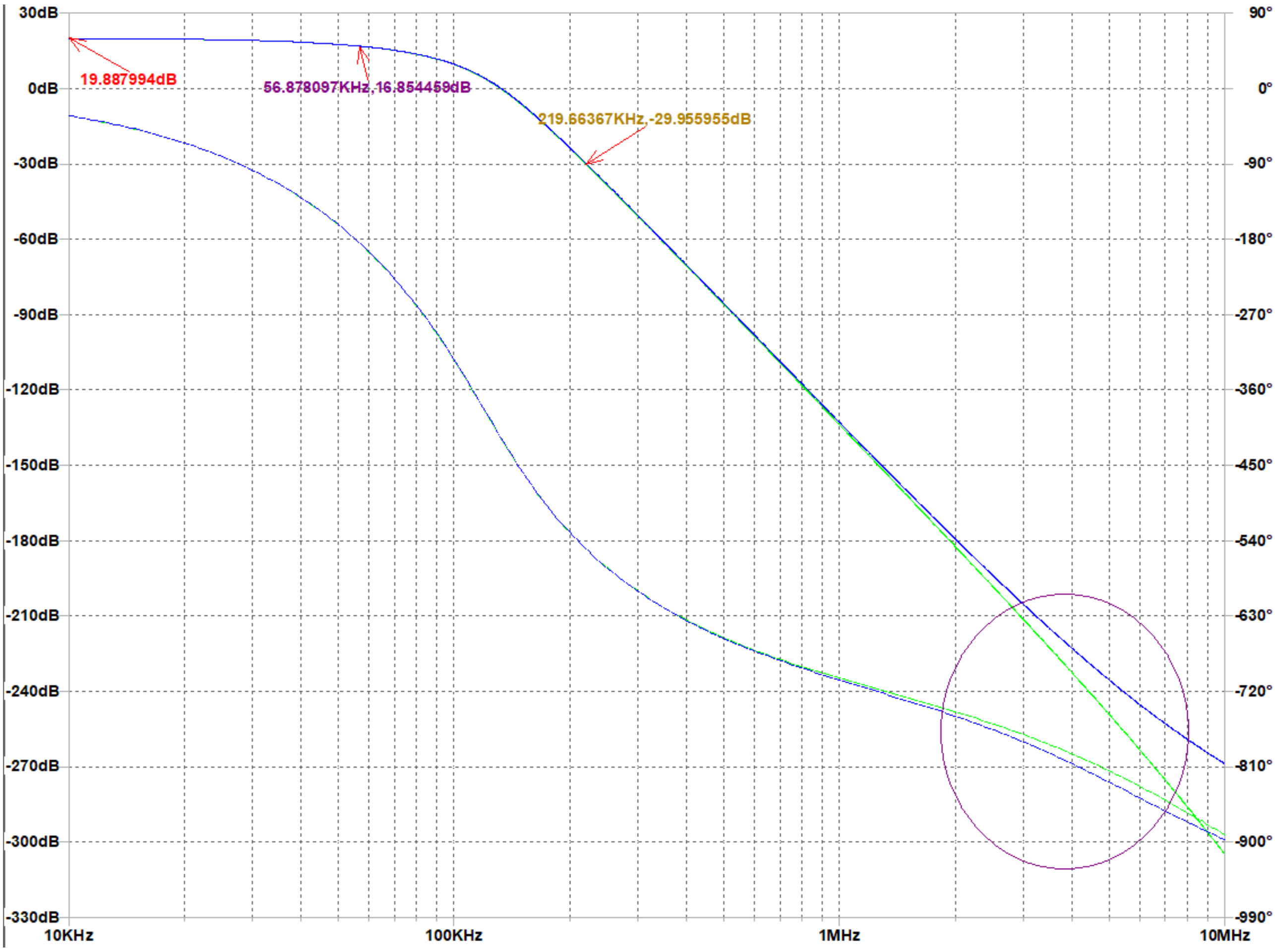

Figure 41: Frequency response

4.16.3 Transient response

Cut-off frequency transient response

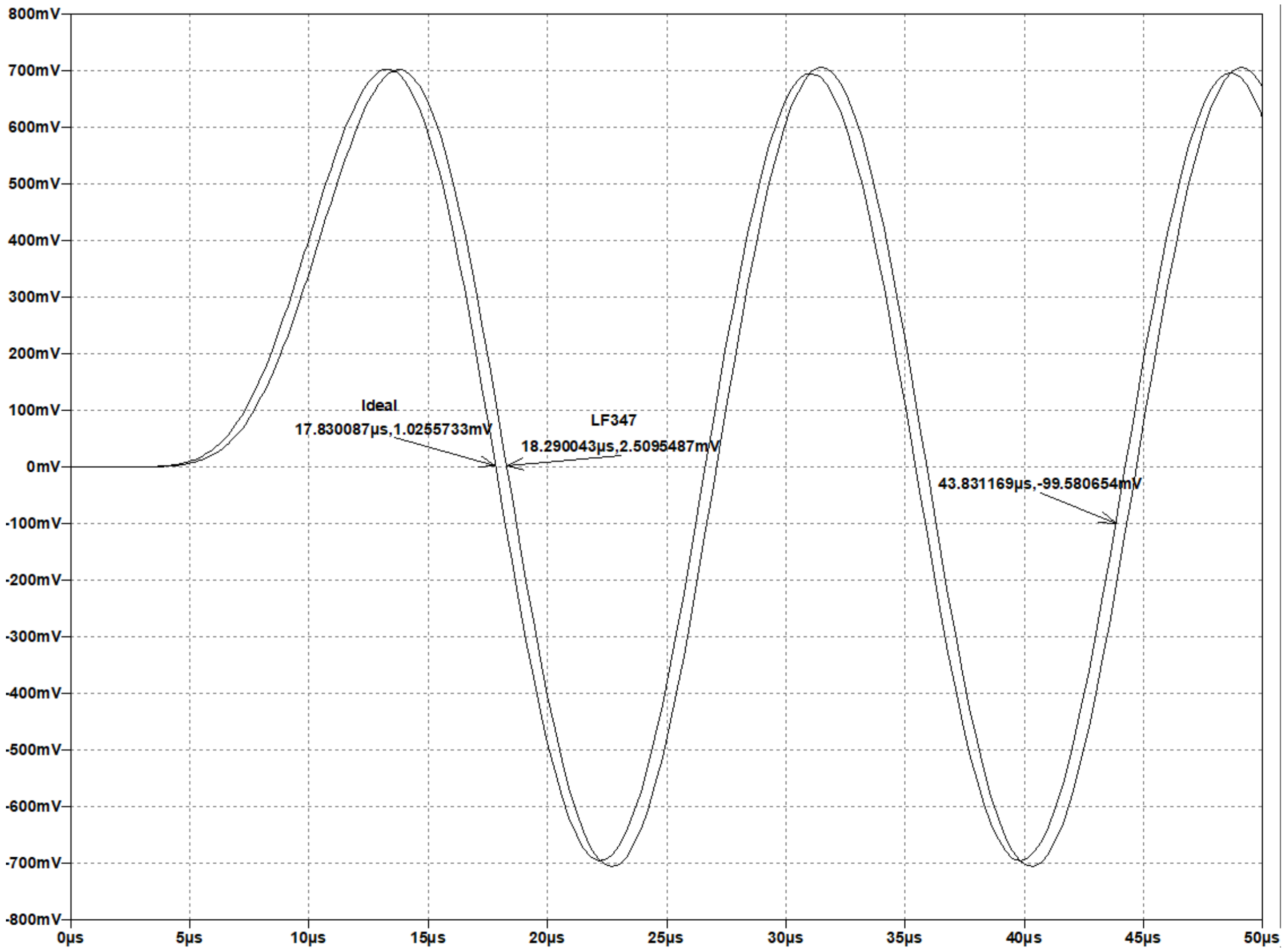

Figure 42: Transient response of phase and gain at cut-off frequency

4.16.4 Copy-paste interpretation of results for approximated components and non-ideal filters

Gain The gain of the LM347 was found to be 12.6V/V and for the MCP604 it was similarly 12V/V. The ideal op-amp had a gain of 12.7V/V.

Roll-off The LM347 was found to have a near identical roll off to the ideal op-amp. The MCP604 was found to have a less than ideal roll off at higher frequencies around 2MHz.

Cut-off

- Ideal is 22.08KHz
- MCP604 is 29.05KHz
- LM347 is 28.82KHz

Design frequency magnitude

- Ideal is 9.48dB
- MCP604 is 19.05d
- LM347 is 19.04dB

Unity frequency (Gain bandwidth product comparison)

- Ideal is 77.35KHz
- MCP604 is 77.64KHz
- LM347 is 76.12KHz

Voltage off-set

- Ideal is 0V
- LM347 is approximately 5-8mV

Phase difference The phase difference was found to be an error 7.8 degrees between the LM347 and Ideal op-amp

4.16.5 Cascade interpretation of results for approximated components and non-ideal filters

Gain The gain of the LM347 was found to be 9.8V/V and for the MCP604 it was similarly 9.87V/V. The ideal op-amp had a gain of 9.9V/V.

Roll-off The LM347 was found to have a near identical roll off to the ideal op-amp. The MCP604 was found to have a less than ideal roll off at higher frequencies around 2MHz. Similarly to the copy-paste design.

Cut-off

- Ideal is 56.6KHz
- MCP604 is 56.8Hz
- LM347 is 56.7KHz

Design frequency magnitude

- Ideal is 16.87dB
- MCP604 is 16.98d
- LM347 is 16.85dB

Unity frequency (Gain bandwidth product comparison)

- Ideal is 199.094KHz
- MCP604 is 219.66KHz
- LM347 is 220.24KHz

Voltage off-set

- Ideal is 0V
- LM347 is approximately 5mV

Phase difference The phase difference was found to be an error 9.41 degrees between the LM347 and Ideal op-amp

5 Discussion of results

5.1 Copy-paste filter

The copy-paste filter was mixed in reception of performance. The filter met the gain set marginally while failed to meet the cut-off frequency. The filter failed to meet the desired cut-off frequency due to being scaled for a second order design. The scaling factor and Q act to damp and shift the poles of the filter. The frequency and Q scaling were not intended to be used in a staged design to make a higher filter accurately. The poles are duplicated and placed at the same location in the complex plane. They are thus exactly on top on each other. The specific scaling quantities are thus more emphasized as they are being raised to a power of four.

However the cut-off error may also be attributed to two other factors of the multifeedback design and Bessel response. The Bessel when used with a scaling frequency is shaped to better fit around the desired cut-off frequency. The scaling frequency as discussed above is misused when taken as the second order scaling value. However the overall Q was not too different to the ideal cascaded filter at a seven percent error. The multifeedback design also leads to the issues of potential rounding and value errors during calculations.

The unity bandwidth linked to the gain bandwidth product is nearly fifty percent smaller than the ideal cascade and thus will to make the most of the feedback design of a multifeedback design. The multifeedback design is meant to be used to make use of the full open loop gain. This is not possible when the bandwidth is being limited as in this design.

The phase shift and attenuation around the design frequency was found to be unstable. The phase shift was half the size of the phase shift present in the cascaded design. This being due to an inconsistent unity gain bandwidth and frequency scaling shifting the desired cut-off frequency further away from 56.8KHz. The phase thus becomes inconsistent in the transfer function. The phase shift also became inconsistent at higher frequencies due to non idealises in the LF347's slew rate. It became inefficient at high frequencies.

Varying the components tolerances used in the physical design showed the greater instability present with the gain more than doubling due to the component tolerance change. A physical op-amp will saturate quickly if this were the case. Keeping tolerances low will prevent the large deviation from design. The rest of the parameters (Q and unity gain) remained similarly constant compared to the ideal. The parameters are more related to the transfer function and poles chosen, and thus are less affected by the physical realization components. Bessel also aids in masking any oscillations which may occur.

5.2 Cascaded filter

The cascaded filter proved to be more accurate to the ideal transfer function. The Bessel function separates its poles evenly in the left hand plane. The scaling and Q factors act independently of one another to each scale a pole in the plane. The frequency and Q factors do not act onto the same single pole like the copy-paste filter. The filter is thus more accurate.

The cut-off frequency however experienced a slight error. This is due to two factors being the dampening factor which is twice the reciprocal of Q. This shifts the frequency when the designer table is used with Bessel. The poles in the left hand plane are thus off set by a certain amount due to the Q factor and frequency scaling. The natural frequency will equate to the cut-off (design frequency) when the dampening factor is exactly a half. The cut-off will otherwise be off-set from the desired cut-off point but the amount should not be too large. A one percent error was determined.

The phase shift at the output was found to be a phase shift of approximately one-hundred and eighty degrees. The Multifeedback design is an integrator design with two loops. It is known to invert it's output which is equivalent to a one-hundred and eighty degree phase shift. The filter also introduces a ninety degree phase shift for each pole of which there are eight. The total and final phase shift is calculated below:
Final-phase-shift:

$$
\begin{aligned}
FS &= 180 * 4 + 90 * 8 && (12)\\
&= 900^\circ && (13)\\
&= 2 * 360^\circ + 180^\circ && (14)\\
&= 180^\circ && (15)\\
& && (16)
\end{aligned}
$$

The phase agreed with simulated results.

Monte Carlo and Non ideal component responses matched similar ranges as the copy-paste design. Due to a more robust design in the frequency and Q factor scaling, the circuit had less deviations from ideal valuations outside of extreme cases in Monte Carlo analysis. The values were all fairly similar to the E96 and ideal cases. The LF347 compared to the MCP604 began to deviate at higher frequencies from the roll-off. This may be due to factors of slew rate limiting of which the LF347 is not as fast as the MCP604 which remained accurate for longer.

The bandwidth is less restricted than the copy-paste design at twice the size following from better scaling the frequency and Q factors. This allows better loop gain and the quality of the gain is better within the design when incorporated with the multi-feedback network.

6 Conclusion

Two eighth order filters were successfully implemented. A second order Bessel multifeedback filter was copy and pasted four times to make an eighth order filter to a certain degree of success. A high order cascaded filter was successfully designed and simulated. A multifeedback circuit was successfully designed and implemented for both filters. Both circuits were investigated using varying physical components and different resistor-capacitor standards. The standards being the E96/E24 and E6/E12 standards and the MCP604 and LM347 op-amps investigated. Monte Carlo analysis was also successfully used for further observation of the cascaded circuit for varying component tolerances. The frequency error was observed for the Bessel filter of the cascaded filter. The cascaded filter was found to have a a closer resemblance to the ideal transfer function response than the copy-paste filter which performed well as a filter but not at the required design requirements.

A Theory questions

A.1 Explain the difference between the natural frequency and the cut-off frequency. How does the relationship between the two vary for Chebyshev and Butterworth responses?

The natural frequency of a filter is the frequency at which the the signal leaves the passband. This is the case for the Chebyshev filter which ripples before leaving the passband past the cut off frequency. The natural frequency may be the same as the cut off frequency. Which is the case for the Butterworth filter. The cut off frequency is the frequency at which the signal lowers to 3dB less than the maximum gain (in dB). This is where the gain is $1/\sqrt{2}$ the maximum gain. No distortion may be picked up by a human ear before this point as the gain reduces.

A.2 Designers need to choose between topologies when implementing their filters. What are some reasons that a designer may choose a KRC filter over a Multiple Feedback filter?

The KRC topology is less sensitive to noise for low freqeuncy operations with low Q values. The sallen key does not invert its input at each stage. Gain accuracy is higher especially when used as a unity gain filter. The amount of components may also be potentially less in this topology.

A.3 Designers need to choose between topologies when implementing their filters. What are some reasons that a designer may choose a Multiple Feedback filter over a KRC filter?

The mutlifeedback is less sensitive to component variations and high Q values being used in it's design. The filter topology is less sensitive to noise as frequency increases. The low pass multifeedback circuit at higher frequencies remains linear in attenuation at higher frequencies while the KRC loses attenuation linearity (and thus accuracy) from the topology of the shunt capacitor. The gain is easier to scale against Q.

A.4 In cascade design, how would one order the different sections?

The recommended order in the prescribed textbook [1]: the sections are ordered in ascending Q values for each section to avoid signal clipping and reduced dynamic range. Additional recommendations were found to be to place the highest Q stage first as to reduce the amount of internal noise which will be affected by the largest Q. Placing first allows the noise not be present or significantly reduced at the final stages output.

B References

References

[1] S. Franco, *Design with operational amplifiers and analog integrated circuits*. McGraw Hill, 2015, ISBN: 978259253133.