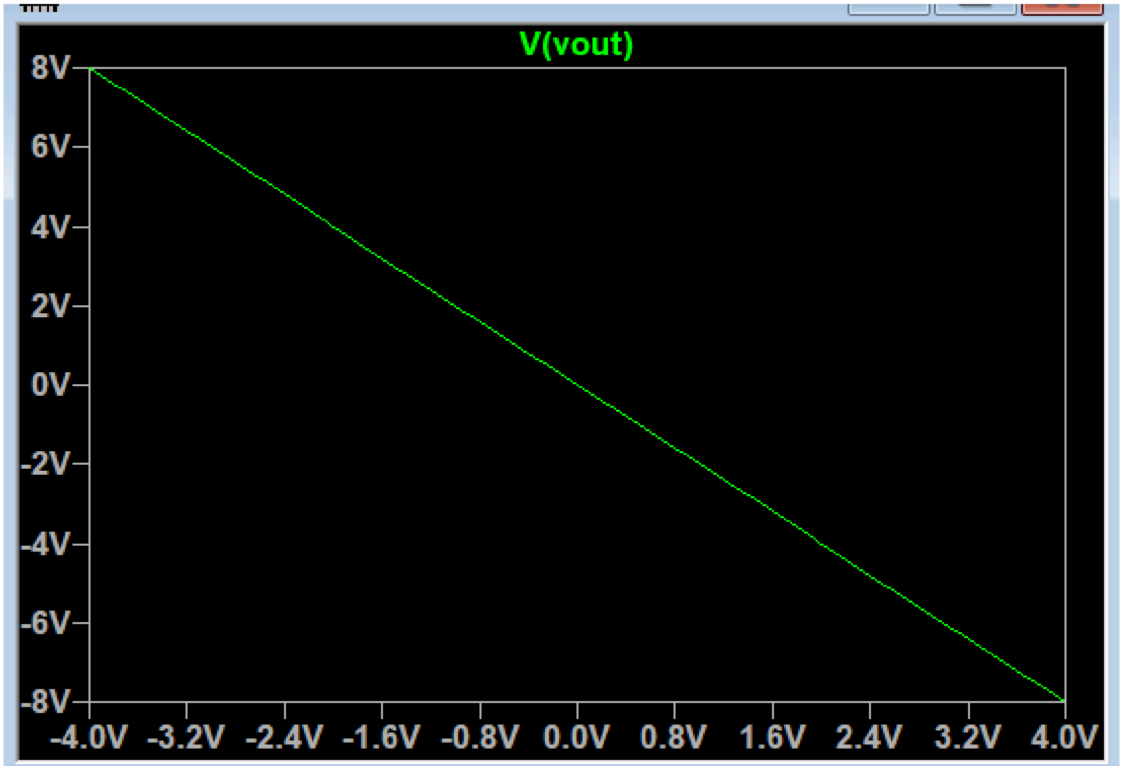
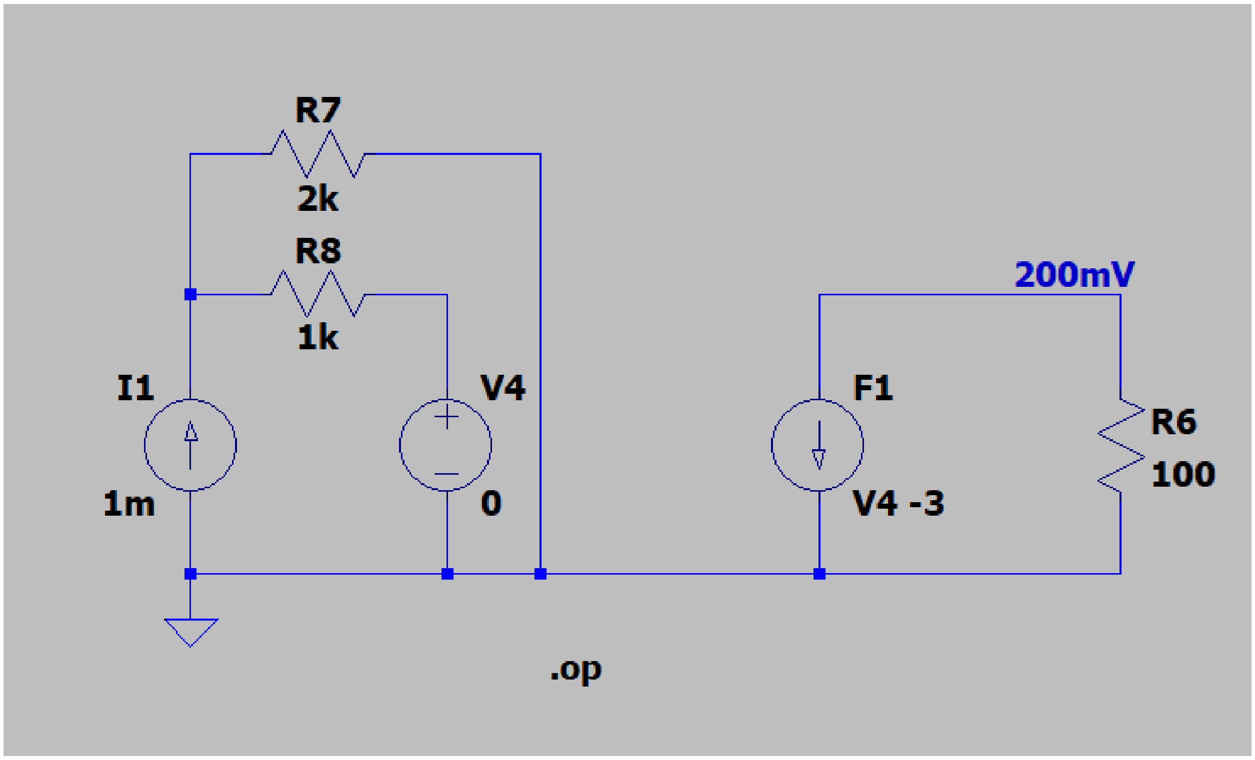
Part 1: VCVS



vout vs vin: The slope -2 is the VCVS’s gain.

Part 2: Current Controlled Devices

Modified CCCS circuit schematic that is -3x of the current in R8:



The updated .op label reading is 200 mV.

Double-check via the .op output:

```
* C:\Users\13764\Documents\LTspice\1.2.1.asc

       --- Operating Point ---

V(n001):         0.666667       voltage
V(n002):         0              voltage
V(n003):         0.2            voltage
I(F1):           -0.002         device_current
I(I1):           0.001          device_current
I(R8):           -0.000666667   device_current
I(R7):           -0.000333333   device_current
I(R6):           0.002          device_current
I(V4):           0.000666667    device_current
```

I (F1): -0.002

Part 3: VCVS Opamp Models

Let E be the VCVS gain.
Theoretical calculation:

$$V_{out} = -E v_N$$

$$\frac{V_N - V_{in}}{1k} + \frac{V_N - V_{out}}{2k} = 0$$

$$-\frac{2}{E} V_{out} - 2V_{in} - \frac{1}{E} V_{out} - V_{out} = 0$$

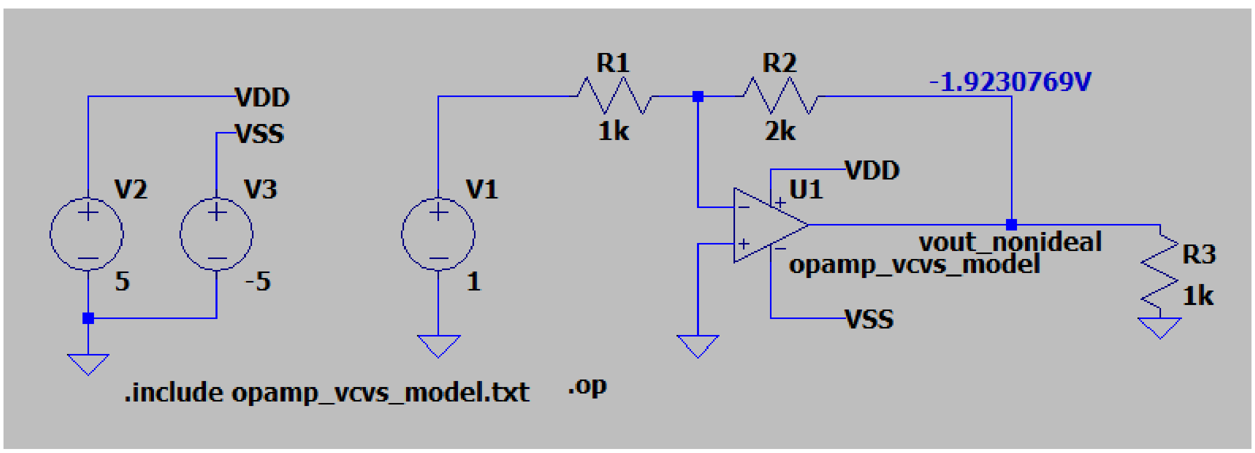
$$-2V_{in} = \left(1 + \frac{3}{E}\right) V_{out}$$

$$V_{out} = -\frac{2E}{E+3} V_{in}$$

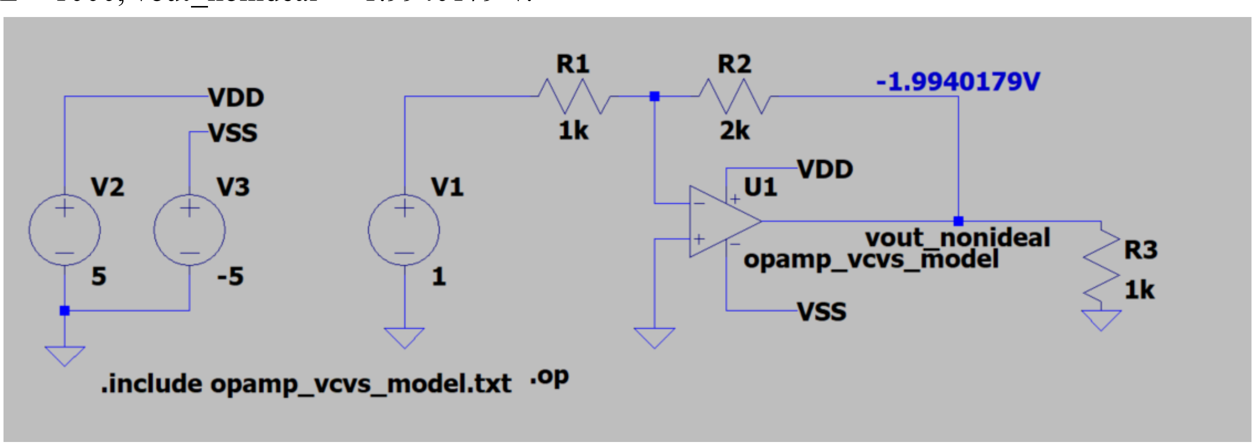
$V_{in} = 1V$:

E	V_{out} (V)
75	-1.92308
1000	-1.99402
1e5	-1.99994

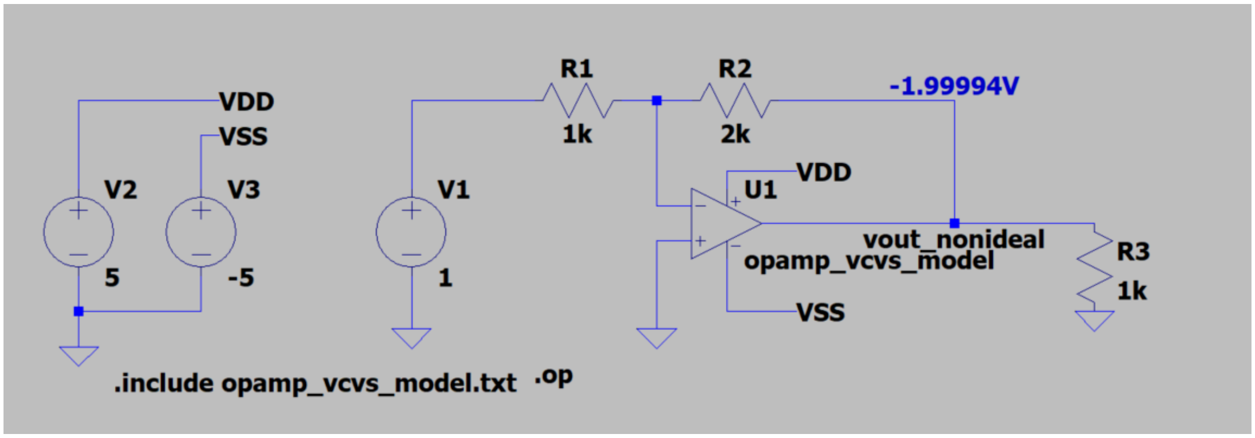
VCVS .op simulation result:
E = 75, vout_nonideal = -1.9230769 V.



E = 1000, vout_nonideal = -1.9940179 V.



E = 1e5, vout_nonideal = -1.99994 V



The calculation matches the simulation result exactly.

For an ideal opamp, where the open-loop gain is infinity, the gain is -2. The output should be -2 V when the input is 1 V. As the actual gain increases and approaches infinity, vout_nonideal approaches -2 V, closer to the ideal behavior

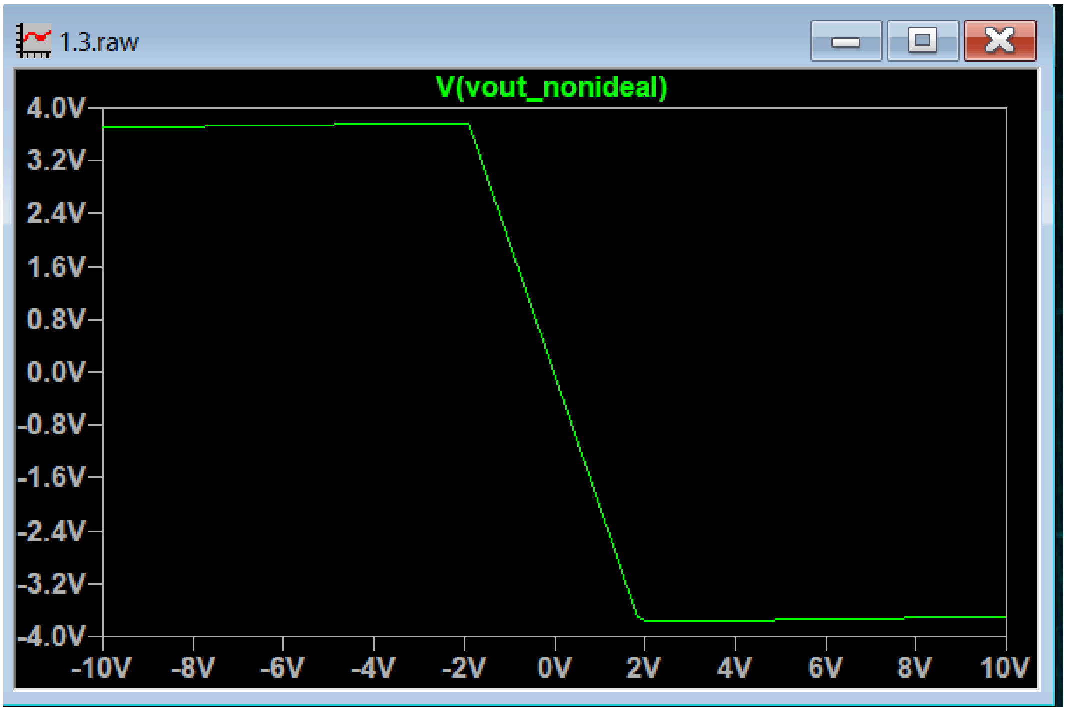
Part 4: Opamp with Saturation

vout saturates at 5 V and -5 V due to the arctangent function.

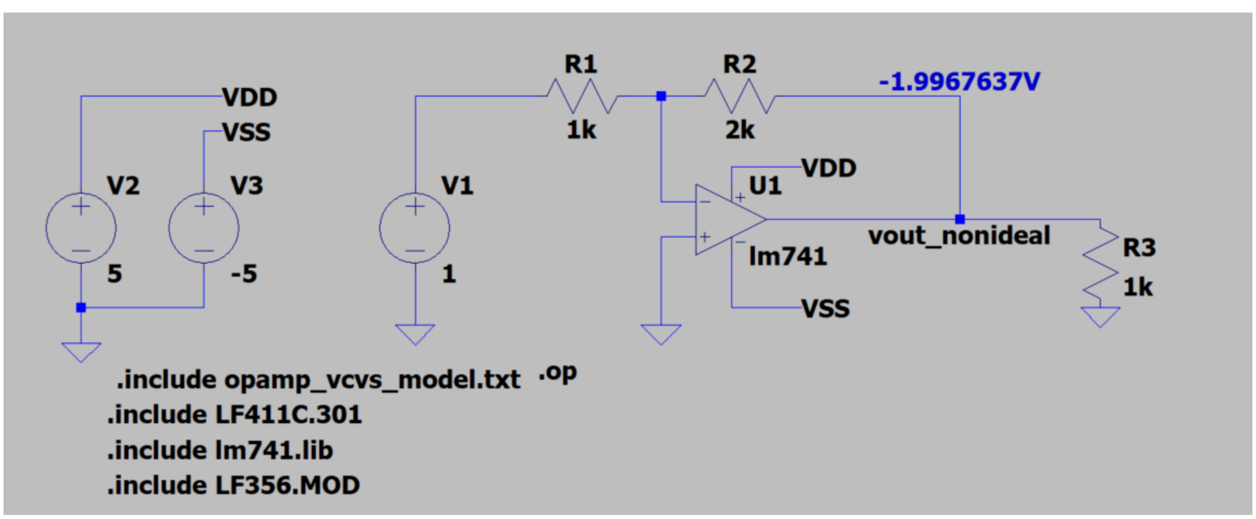
Part 5: Commercial Opamp Model

LM741

DC sweep curve:



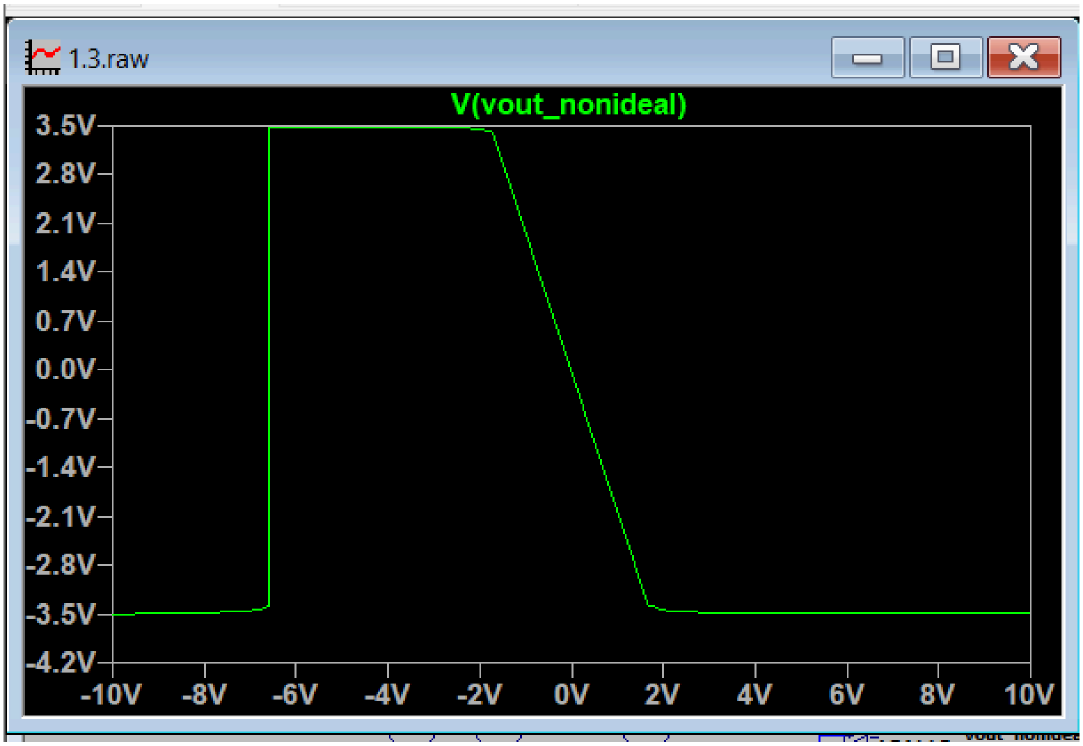
From the DC sweep curve, the output range is approximately -3.7 V to 3.7 V. The curve has sharp corners, very ideal.



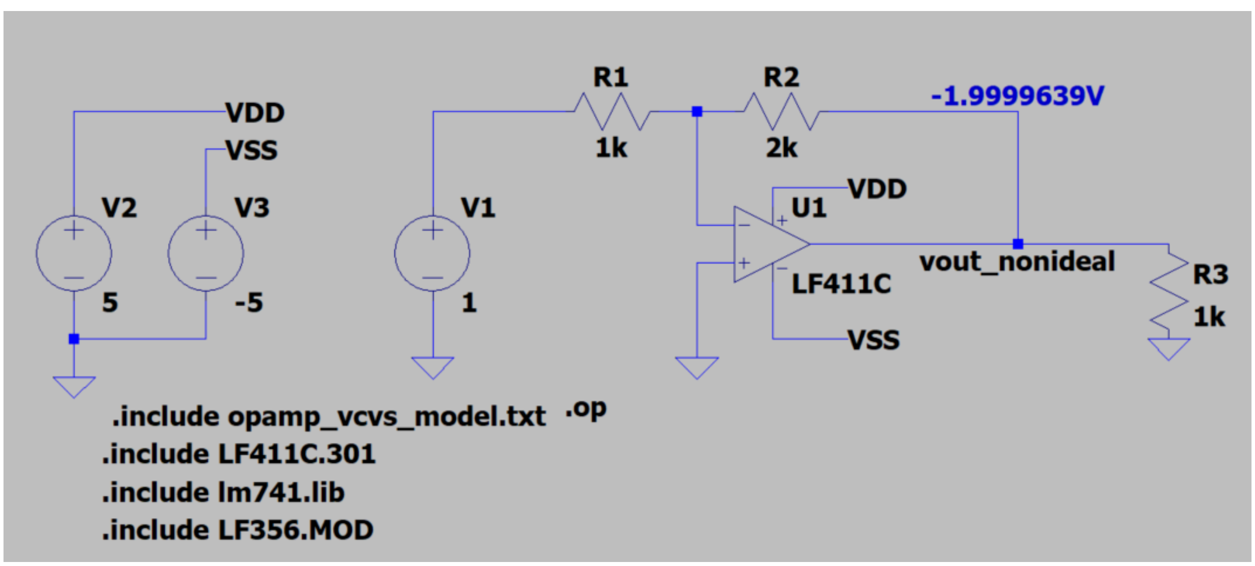
vout_nonideal = -1.9967637 V, 99.84% of the ideal gain.

LF411C

DC sweep curve:



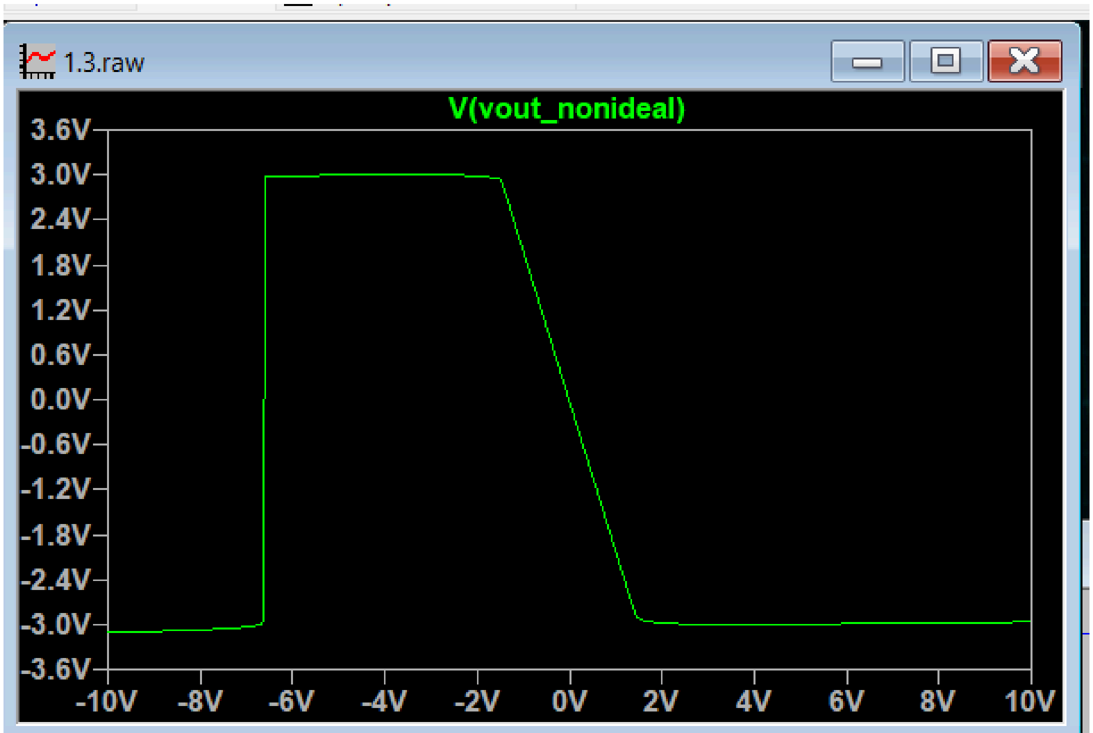
The output range is approximately -3.5 V to 3.5V. The corners are round, so there is some distortion before saturation. 1 V is in the linear region, so this does not affect our gain.



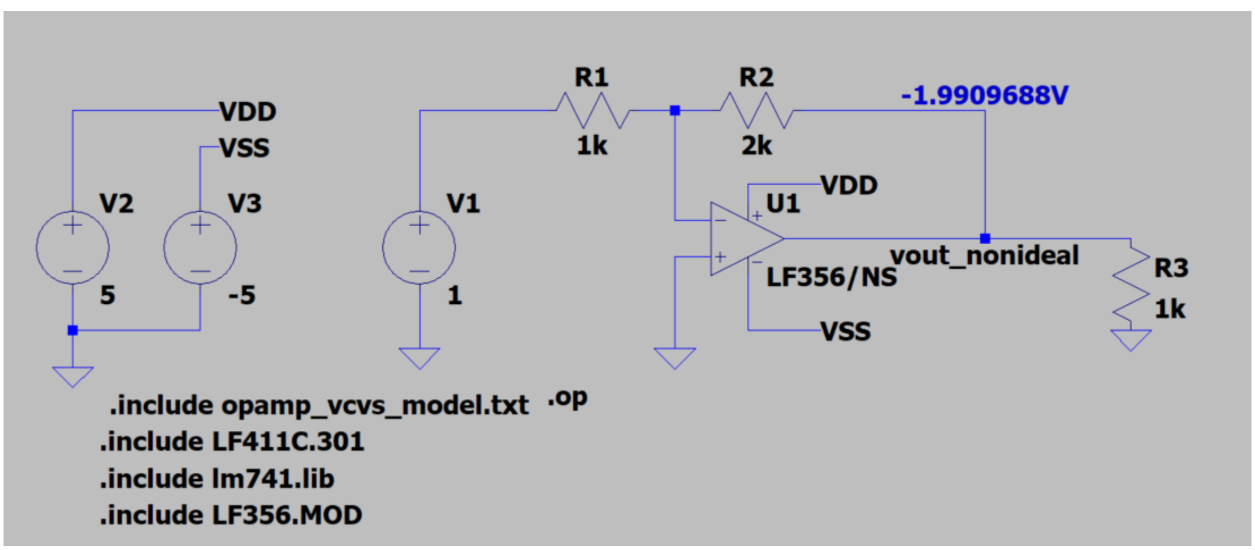
vout_nonideal = -1.9999639 V, 99.997% of the ideal gain

LF356/NS

DC sweep curve:



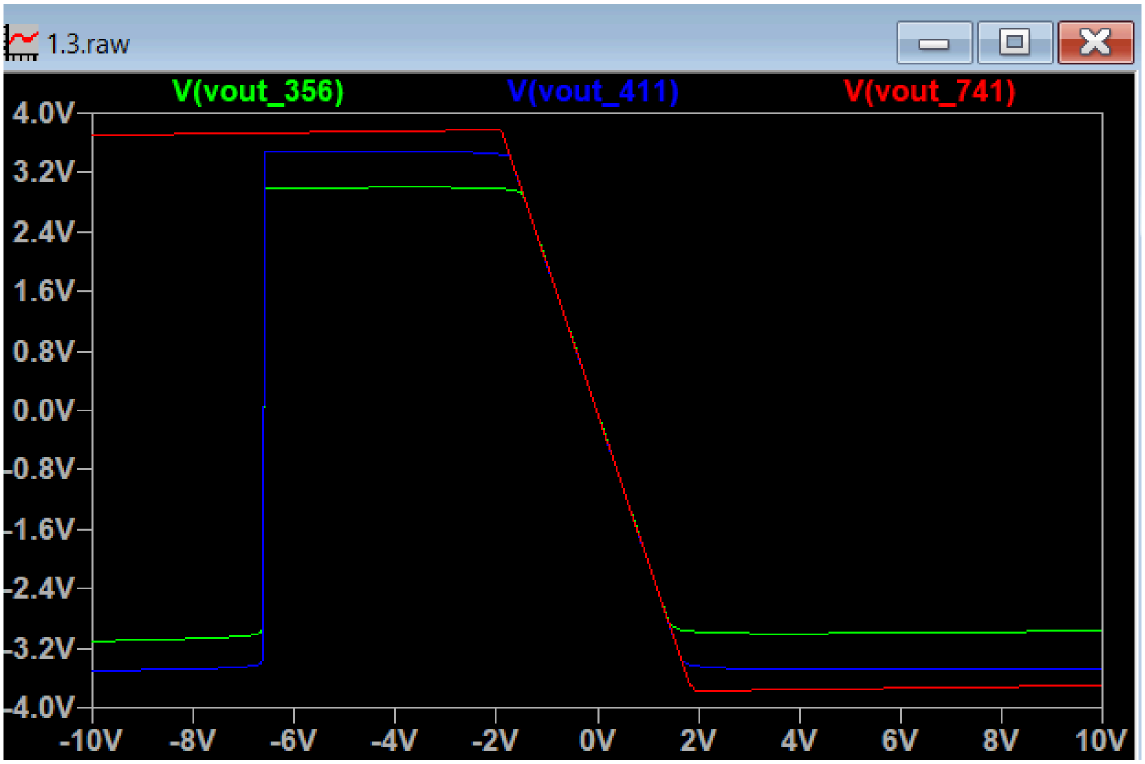
The output range is approximately -3 V to 3 V. Similar to LF411C, the corners are not sharp before saturation.



vout_nonideal = -1.9909688 V, 99.55% of the ideal gain.

Summary

Superimposing all three curves:

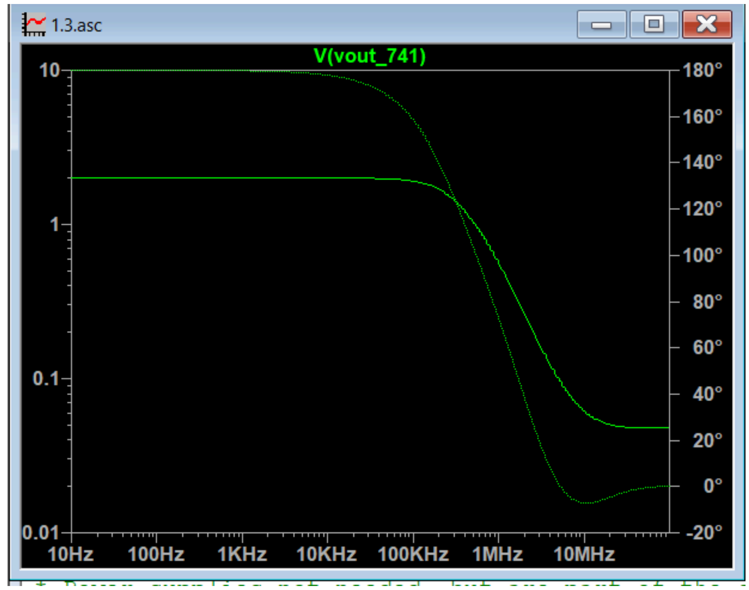


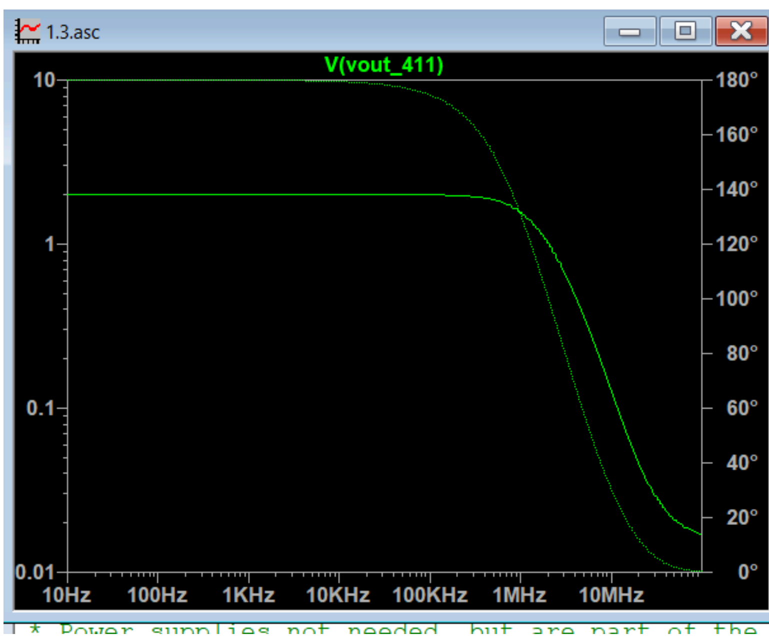
In terms of output voltage vout_nonideal in the circuits above, LF411C's output is the closest to ideal, at 99.997% of the ideal gain.

In terms of DC sweep curve shape, LM741 gives the most ideal output. Its curve has sharper corners, so it still maintains an ideal (linear) output voltages close to saturation.

LM741 also gives the widest output range of approximately -3.7 V to 3.7 V.

Part 6: AC Analysis

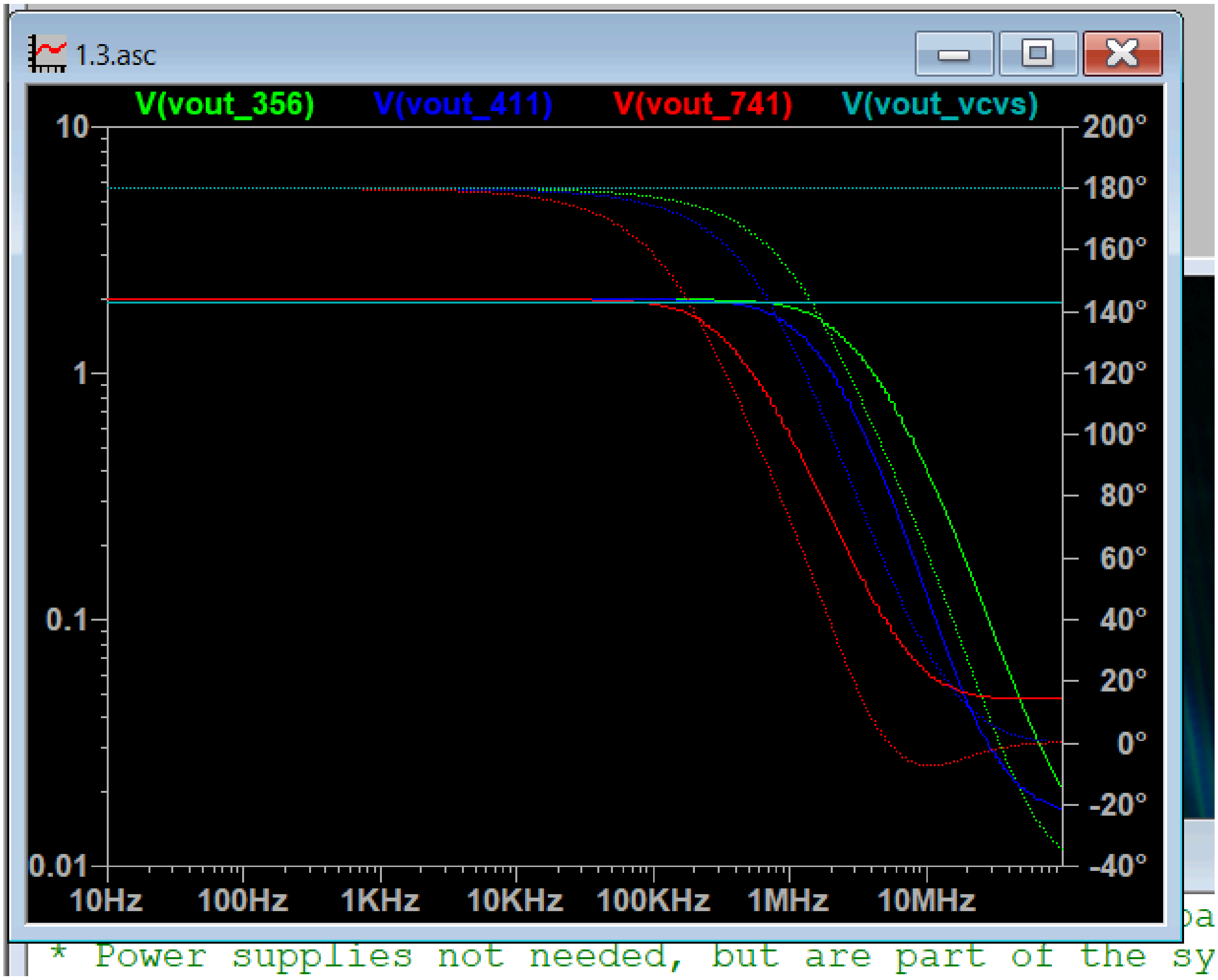




Above are the AC analyses of the four op amp models.

Summary

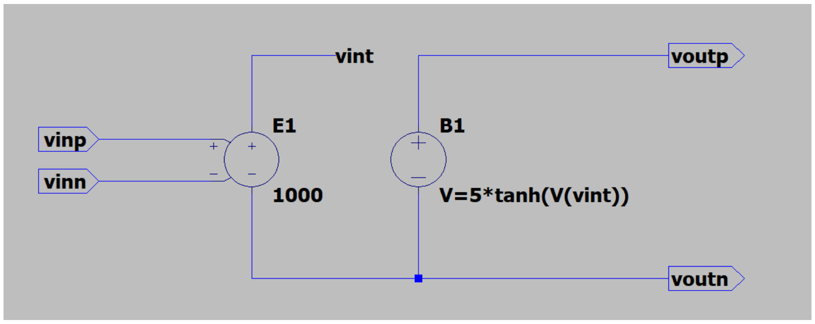
For comparison, I superimposed the four curves.



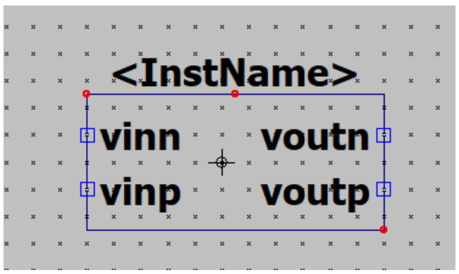
Among the commercial models, LF356 (green) has the widest frequency response, up to about 1 MHz, until the gain declines significantly below 2.

Part 7: Subcircuit

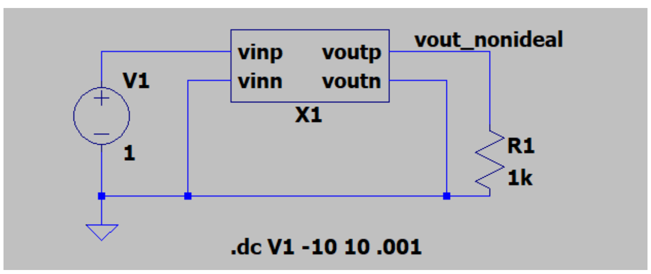
Subcircuit schematic:



Subcircuit symbol:



Circuit schematic:



DC sweep plot: