[redacted]

1)

a.

$$V_{out} = VDD - \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{in} - V_{TH})^2 R_L = f(V_{in})$$

$$= f(V_{in0}) + f'(V_{in0})(V_{in} - V_{in0}) + \frac{f''(V_{in0})}{2!}(V_{in} - V_{in0})^2 + \frac{f'''(V_{in0})}{3!}(V_{in} - V_{in0})^3 + \cdot\ \cdot$$

$$\text{small voltage gain} = f'(V_{in0}) = -\mu_n C_{ox}\frac{W}{L}(V_{in0} - V_{TH})R_L$$

b.

$$\mathrm{V}_{n,in}^2 = \frac{4kTg_{m1} + \frac{4kT}{R_L}}{g_{m1}^2} \quad (\mathrm{V}^2/\mathrm{Hz})$$

c.

$$V_{in} = V_{in0} + V_m \cos\omega t$$

$$\Delta V_{out} = f'(V_{in0})V_m \cos\omega t + \frac{f''(V_{in0})}{2!}(V_m \cos\omega t)^2 + \cdot\ \cdot$$

$$@\omega \rightarrow \mu_n C_{ox}\frac{W}{L}(V_{in0} - V_{TH})R_L V_m \cos\omega t \rightarrow \text{amplitude} = \mu_n C_{ox}\frac{W}{L}(V_{in0} - V_{TH})R_L V_m \quad \#$$

$$@2\omega \rightarrow \frac{1}{4}\mu_n C_{ox}\frac{W}{L}R_L V_m^2 \cos 2\omega t \rightarrow \text{amplitude} = \frac{1}{4}\mu_n C_{ox}\frac{W}{L}R_L V_m^2 \quad \#$$

d.

$$\mathrm{THD} = \left(\frac{V_m}{4(V_{in0} - V_{TH})}\right)^2 \rightarrow M_1\text{的}\frac{\mathrm{W}}{L}\text{愈大，}V_{in0} - V_{TH}\text{愈小，使得 harmonic distortion 愈大}$$

e.

$$\mathrm{V}_{n,in}^2 = \frac{4kT\gamma g_{m1} + \frac{4kT}{R_L}}{g_{m1}^2} = \frac{4kT\gamma}{g_{m1}} + \frac{4kT}{g_{m1}^2 R_L} = \frac{4kT\gamma}{2\sqrt{\frac{1}{2}\mu_n C_{ox}\frac{W}{L}I_D}} + \frac{4kT}{2\mu_n C_{ox}\frac{W}{L}I_D R_L}$$

$$\rightarrow M_1\text{的}\frac{\mathrm{W}}{L}\text{愈大，input} - \text{reffered noise 愈小}$$

f.

```
**** mosfets


 subckt
 element  0:m1
 model    0:n_18.1
 region     Saturati
  id        999.9515u
  ibs      -1.661e-19
  ibd      -559.0985a
  vgs       900.0000m
  vds       900.0436m
  vbs         0.
  vth       492.5708m
  vdsat     275.8482m
  vod       407.4292m
  beta       15.2471m
  gam eff   507.4534m
  gm          3.4755m
  gds       190.7101u
  gmb       502.2509u
  cdtot      10.0544f
  cgtot      14.5088f
  cstot      20.7276f
  cbtot      18.5332f
  cgs        10.4989f
  cgd         2.8090f
```

DC current

Vout

g.

```
M1 Vout Vin VSS VSS N_18 W=7.779u L=180n m=1
```

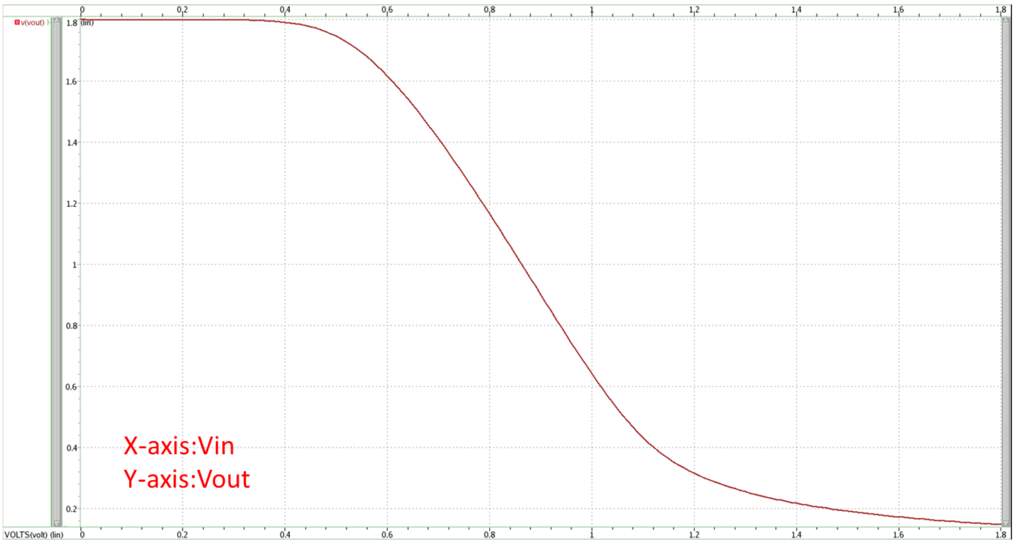
Size

$V_{GS} - V_{TH} = V_{OV} = 0.9 - 0.4926 \cong 0.407 \ (V)$

```
****** ac analysis tnom=  25.000 temp=  25.000 ******
gmax=   8.5207      at=    1.0000k
             from=   1.0000k    to= 100.0000g
gain=   8.5207
bw=  20.8217g
```

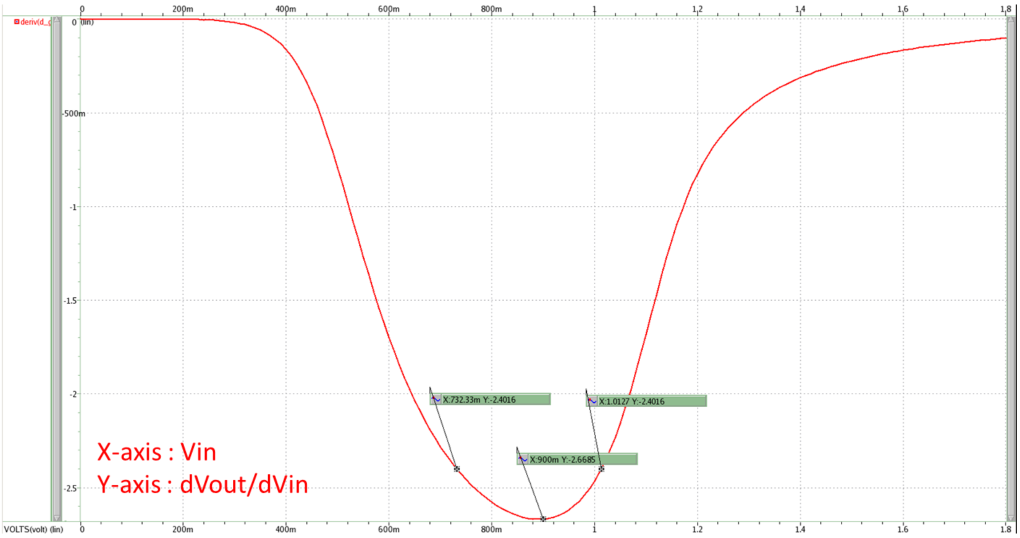
gain=8.5207dB

h.



i.

透過對 Vout 一次微分，找與 operation point=0.9V 斜率，誤差 10%的範圍



Vin range=(732.33mV , 1.0127V) #

j.

Vin 太大: 逐漸進入 triode region

Vin 太小: 逐漸進入 cut-off region

k.

$$\text{THD} = \left(\frac{V_m}{4(V_{in0} - V_{TH})}\right)^2 = \left(\frac{0.025}{4 \times (0.9 - 0.4926)}\right)^2 = 2.3535 \times 10^{-4}$$

l.

@1MHz:-22.613dB

@2MHz:-83.724dB

m.

$$\mathrm{THD} = [-83.724 - (-22.613)] \times 2 = -122.222\mathrm{dB}$$

n.

Calculated:

$$\mathrm{THD} = 20\log 2.3535 \times 10^{-4} = -72.566\mathrm{dB}$$

Simulated:

$$\mathrm{THD} = -122.222\mathrm{dB}$$

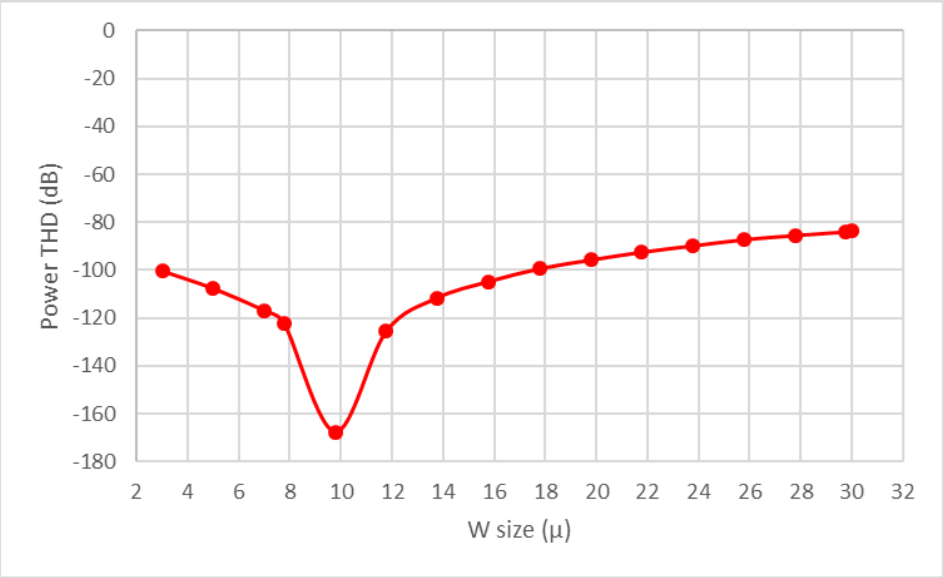
差異原因:

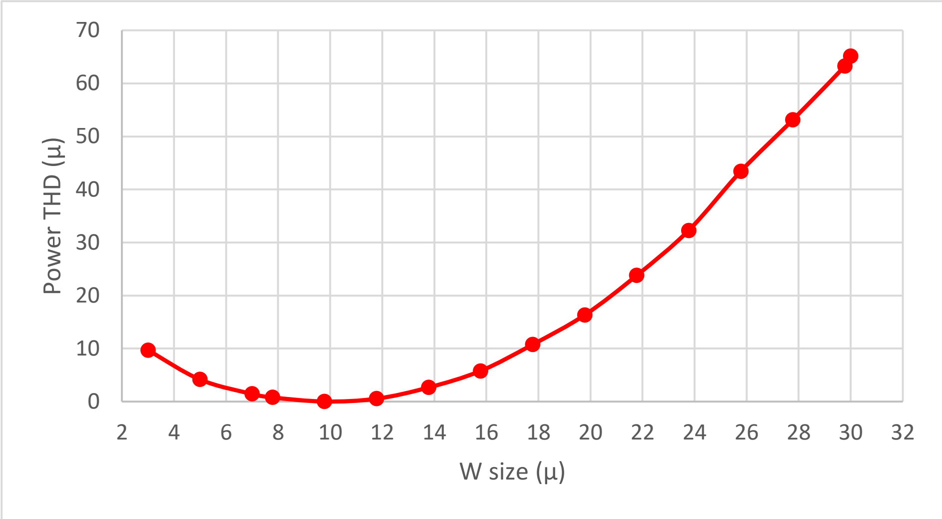
1.可能是 1MHz 的訊號已超過頻寬導致模擬結果變好，但 CS 架構頻寬高並非此原因。

2.在 I_D 計算時過程時忽略了 channel length modulation 和 body effect 等因素，導致計算的不精準造成差異。

o.

Vin (V)	W size	I_D (A)	A_F (dB)	A_{HD2} (dB)	Power THD (dB)
Vin=1.319	W=3.000u	I_D=1.0001m	A_F=-29.362	A_{HD2}=-79.502	-100.28
Vin=1.054	W=5.000u	I_D=1.0004m	A_F=-25.541	A_{HD2}=-79.363	-107.644
Vin=0.932	W=7.000u	I_D=1.0001m	A_F=-23.284	A_{HD2}=-81.726	-116.884
Vin=0.9	W=7.779u	I_D=1.0000m	A_F=-22.613	A_{HD2}=-83.724	-122.222
Vin=0.839	W=9.779u	I_D=0.9995m	A_F=-21.218	A_{HD2}=-105.012	-167.588
Vin=0.797	W=11.779u	I_D=1.0009m	A_F=-20.130	A_{HD2}=-82.925	-125.59
Vin=0.765	W=13.779u	I_D=0.9987m	A_F=-19.287	A_{HD2}=-75.070	-111.566
Vin=0.741	W=15.779u	I_D=1.0011m	A_F=-18.553	A_{HD2}=-70.948	-104.79
Vin=0.721	W=17.779u	I_D=1.0001m	A_F=-17.963	A_{HD2}=-67.657	-99.388
Vin=0.705	W=19.779u	I_D=1.0023m	A_F=-17.429	A_{HD2}=-65.308	-95.758
Vin=0.691	W=21.779u	I_D=1.0017m	A_F=-16.989	A_{HD2}=-63.231	-92.484
Vin=0.679	W=23.779u	I_D=1.0015m	A_F=-16.600	A_{HD2}=-61.513	-89.826
Vin=0.668	W=25.779u	I_D=0.9980m	A_F=-16.289	A_{HD2}=-59.915	-87.252
Vin=0.659	W=27.779u	I_D=0.9993m	A_F=-15.966	A_{HD2}=-58.714	-85.496
Vin=0.651	W=29.779u	I_D=1.0008m	A_F=-15.673	A_{HD2}=-57.662	-83.978
Vin=0.650	W=30.000u	I_D=0.9998m	A_F=-15.654	A_{HD2}=-57.515	-83.722





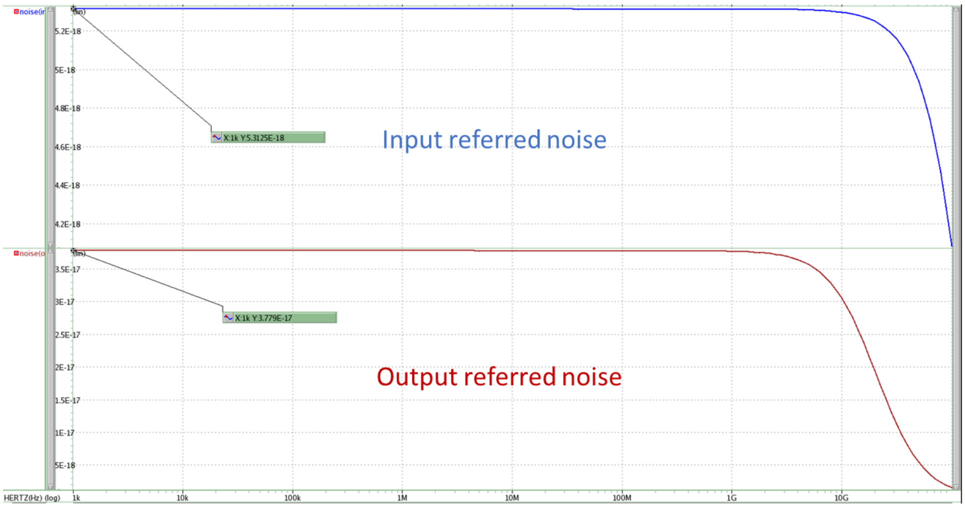
p.

$$\text{THD} = \left(\frac{V_m}{4(V_{ino} - V_{TH})}\right)^2 \rightarrow M_1\text{的}\frac{\mathrm{W}}{L}\text{愈大，}V_{ino}\text{愈小，使得 harmonic distortion 愈大}$$

$$\left(\frac{1}{V_{ino - V_{TH}}}\right)^2 \propto \frac{W}{L}$$，因此未取 20dB 時圖應該呈線性，斜率應該為正

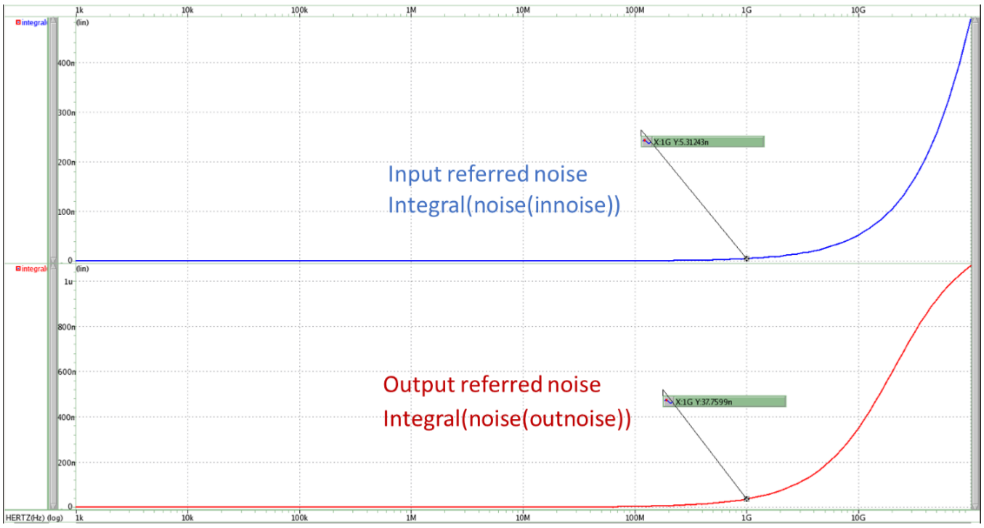
在 W 在 10 μ 以下時與預期不同，主要是 A_{HD2} 的變化不如預期，猜測的原因是 noise，但 noise 影響又不至於在單一頻率下有很大的差別，因此推測可能也是 I_D 計算時過程時忽略了 channel length modulation 和 body effect 等因素；且 W 愈小時已經慢慢進入 triode region，I_D 也應該要漸漸換成 triode region 的公式。

q.



$\text{Input referred noise} = 5.313 \times 10^{-18}\ (\mathrm{V}^2/\mathrm{Hz})$

$\text{Output referred noise} = 3.779 \times 10^{-17}\ (\mathrm{V}^2/\mathrm{Hz})$

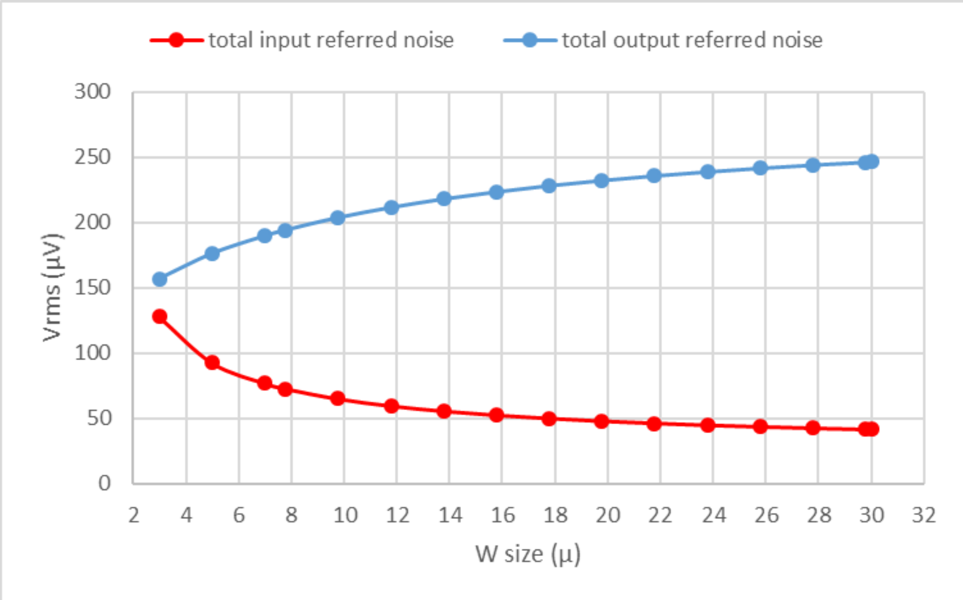


$\text{Total input referred noise} = 5.312\text{n} \ (\text{V}^2) = (7.288 \times 10^{-5} V_{rms})^2$

$\text{Total output referred noise} = 37.760\text{n} \ (\text{V}^2) = (1.943 \times 10^{-4} V_{rms})^2$

r.

Vin (V)	W size	I_D (A)	Input noise (V_{rms})	Output noise(V_{rms})
Vin=1.319	W=3.000u	I_D=1.0001m	128.101u	156.985u
Vin=1.054	W=5.000u	I_D=1.0004m	92.687u	176.325u
Vin=0.932	W=7.000u	I_D=1.0001m	76.974u	189.937u
Vin=0.9	W=7.779u	I_D=1.0000m	72.886u	194.319u
Vin=0.839	W=9.779u	I_D=0.9995m	65.113u	203.915u
Vin=0.797	W=11.779u	I_D=1.0009m	59.717u	211.687u
Vin=0.765	W=13.779u	I_D=0.9987m	55.748u	218.208u
Vin=0.741	W=15.779u	I_D=1.0011m	52.644u	223.650u
Vin=0.721	W=17.779u	I_D=1.0001m	50.183u	228.353u
Vin=0.705	W=19.779u	I_D=1.0023m	48.139u	232.383u
Vin=0.691	W=21.779u	I_D=1.0017m	46.448u	235.928u
Vin=0.679	W=23.779u	I_D=1.0015m	45.008u	239.038u
Vin=0.668	W=25.779u	I_D=0.9980m	43.795u	241.811u
Vin=0.659	W=27.779u	I_D=0.9993m	42.699u	244.241u
Vin=0.651	W=29.779u	I_D=1.0008m	41.730u	246.410u
Vin=0.650	W=30.000u	I_D=0.9998m	41.640u	246.642u



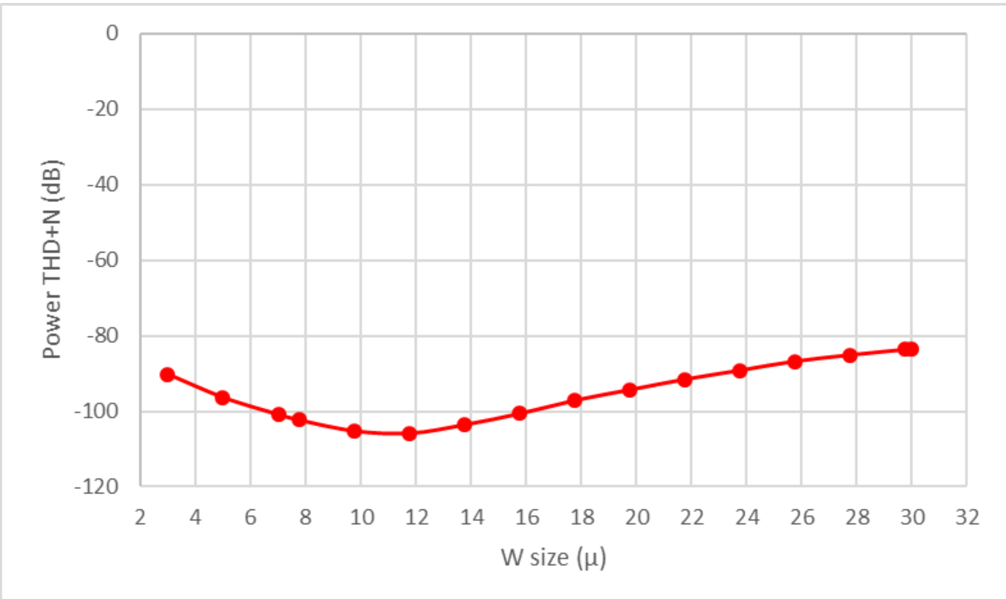
s.

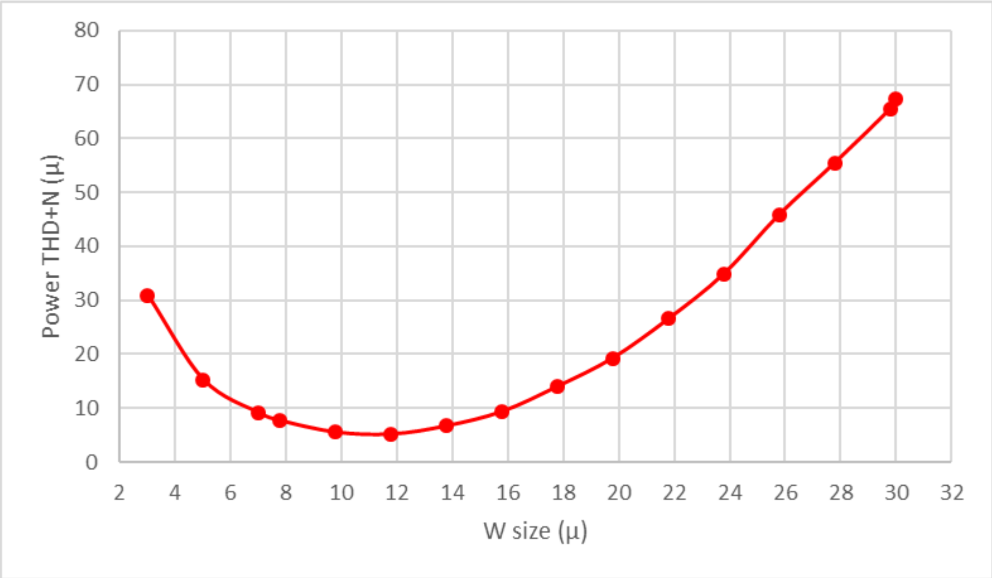
$$V_{n,in}^2 = \frac{4kT\gamma g_{m1} + \frac{4kT}{R_L}}{g_{m1}^2} = \frac{4k\gamma T}{g_{m1}} + \frac{4kT}{g_{m1}^2 R_L} = \frac{4k\gamma T}{2\sqrt{\frac{1}{2}\mu_n C_{ox}\frac{W}{L}I_D}} + \frac{4kT}{2\mu_n C_{ox}\frac{W}{L}I_D R_L}$$

$$V_{n,out}^2 = \left(4kT\gamma g_{m1} + \frac{4kT}{R_L}\right)R_L^2 = 8kT\gamma R_L^2\sqrt{\frac{1}{2}\mu_n C_{ox}\frac{W}{L}I_D} + 4kTR_L$$

因此$V_{n,in}^2$會隨著W變大而減小，$V_{n,out}^2$則會因W變大而減大，模擬結果和想像的趨勢一樣，而計算的比較，由於沒有γ值，無法做明確的計算去比較，且當一個參數無法確定時也難推測其他參數造成的影響。

t.



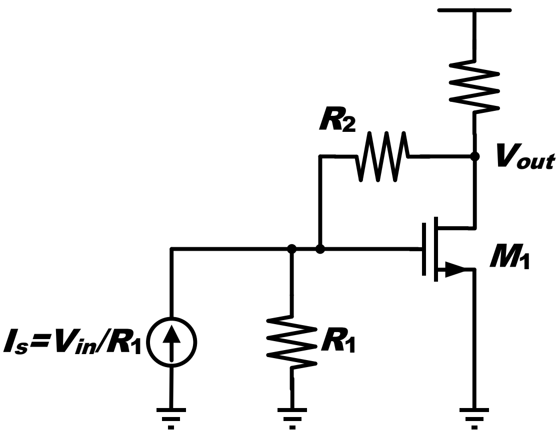


W size 在區間 (11.5 μ , 12.5 μ)有最小的 THD+N ratio，由於 2 μ m 的 step size 去掃，無法很精準地給精確解，但落在這區間內。

2)

a.

Shunt-Shunt feedback 電路，輸入要改成電流源



$$A = -(R_1//R_2) \times g_{m1} \times (R_L//R_2)$$

$$g_{m1} = \mu_n C_{ox} \frac{W}{L}(V_{in0} - V_{TH})$$

$$\beta = -\frac{1}{R_2}$$

$$\text{loop gain} = A\beta$$

$$\frac{V_{out}}{I_S} = \frac{A}{1 + A\beta}$$

$$\text{closed loop gain} = \frac{V_{out}}{V_{in}} = \frac{A}{1 + A\beta} \times \frac{1}{R_1}$$

b.

$$\Delta V_{out} = -(R_1//R_2)\times \mu_n C_{ox}\frac{W}{L}(V_{in0}-V_{TH})\times(R_L//R_2)\times\left(\frac{V_m\cos\omega t}{R_1}-\beta y(t)\right)$$

$$-\frac{1}{2}(R_1//R_2)\times \mu_n C_{ox}\frac{W}{L}\times(R_L//R_2)\times\left(\frac{V_m\cos\omega t}{R_1}-\beta y(t)\right)^2$$

$$\alpha_1 = -(R_1//R_2)\times \mu_n C_{ox}\frac{W}{L}(V_{in0}-V_{TH})\times(R_L//R_2)$$

$$\alpha_2 = -\frac{1}{2}(R_1//R_2)\times \mu_n C_{ox}\frac{W}{L}\times(R_L//R_2)$$

$$@\omega \rightarrow a = \frac{\alpha_1}{1+\beta\alpha_1}\frac{V_m}{R_1}$$

$$@2\omega \rightarrow b = \frac{\alpha_2 V_m^2}{2R_1^2}\frac{1}{(1+\beta\alpha_1)^3}$$

$$\frac{A_{HD2}}{A_F} = \frac{b}{a} = \frac{\alpha_2 V_m}{2R_1}\frac{1}{\alpha_1}\frac{1}{(1+\beta\alpha_1)^2}$$

c.

$$\text{without feedback} \rightarrow \frac{A_{HD2}}{A_F} = \frac{\alpha_2 V_m}{2\alpha_1}$$

with feedback: low THD, low gain, r_{out}變小, r_{in}變小

d.

$$\text{closed loop gain} = \frac{A}{1+A\beta}\times\frac{1}{R_1} = -\frac{R_2}{R_1} = -10$$

e.

```
**** mosfets


 subckt
 element  0:m1
 model    0:n_18.1
 region     Saturati
  id        999.9600u    DC current
  ibs      -1.661e-19
  ibd      -559.0920a
  vgs       900.0030m
  vds       900.0330m    Vout
  vbs          0.
  vth       492.5711m
  vdsat     275.8491m
  vod       407.4319m
  beta       15.2471m
  gam eff   507.4534m
  gm          3.4755m
  gds       190.7127u
  gmb       502.2515u
  cdtot      10.0544f
  cgtot      14.5088f
  cstot      20.7276f
  cbtot      18.5332f
  cgs        10.4989f
  cgd         2.8090f
```

滿足

$R_2 = 10 \cdot R_1$

$R_1 + R_2 > 10 \cdot R_L$

```
**** resistors

subckt
element  0:rl         0:r1         0:r2
 r value  900.0000     900.0000       9.0000k
 v drop   899.9670m    -3.0029u     -30.0291u
 current  999.9633u    -3.3366n      -3.3366n
 power    899.9339u    10.0194f     100.1942f
```

f.

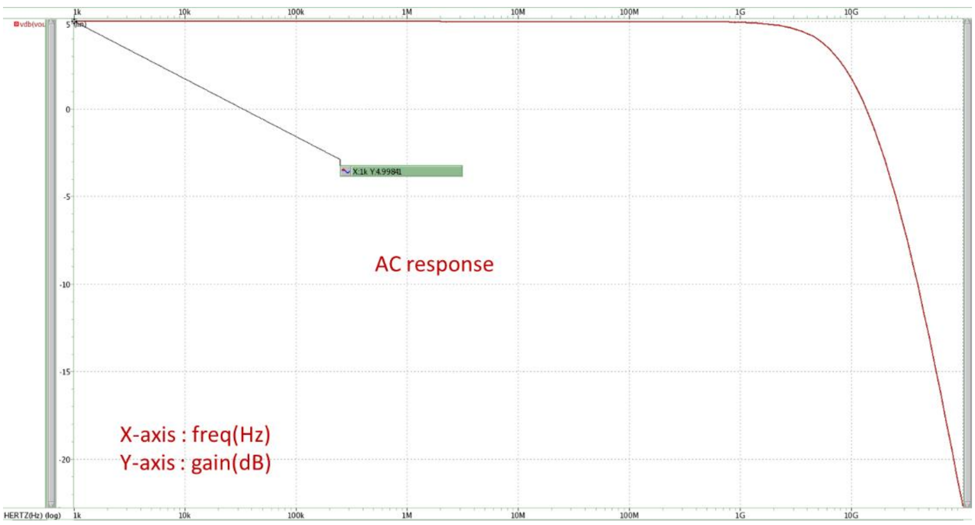
```
RL Vdd Vout 900
R1 Vin Vin1 900
R2 Vin1 Vout 9000
M1 Vout Vin1 VSS VSS N_18 W=7.779u L=180n m=1
```

R1 and R2 value

M1 size

$V_{ov} = V_{GS} - V_{TH} = 0.4074 \ \ (V)$

g.



Simulated:

$\text{small} - \text{signal voltage gain} = 4.998\text{dB}$

Calculated:

$$\text{closed loop gain} = \frac{A}{1+A\beta} \times \frac{1}{R_1} \cong -\frac{R_2}{R_1} = -10 = 20\text{dB}$$

差別在於模擬時$A\beta$並沒有>>1，甚至比 1 小不符合在計算時的假設。

h.

$$\text{without feedback} \rightarrow \frac{A_{HD2}}{A_F} = \frac{\alpha_2 V_m}{2\alpha_1}$$

$$\text{with feedback} \rightarrow \frac{A_{HD2}}{A_F} = \frac{b}{a} = \frac{\alpha_2 V_m}{2R_1}\frac{1}{\alpha_1}\frac{1}{(1+\beta\alpha_1)^2}$$

$$\text{improvement in linearity (power)} \rightarrow \text{兩者相除後平方} \rightarrow \left(\frac{1}{R_1(1+\beta\alpha_1)^2}\right)^2 = \frac{1}{R_1^2(1+\beta\alpha_1)^4}$$

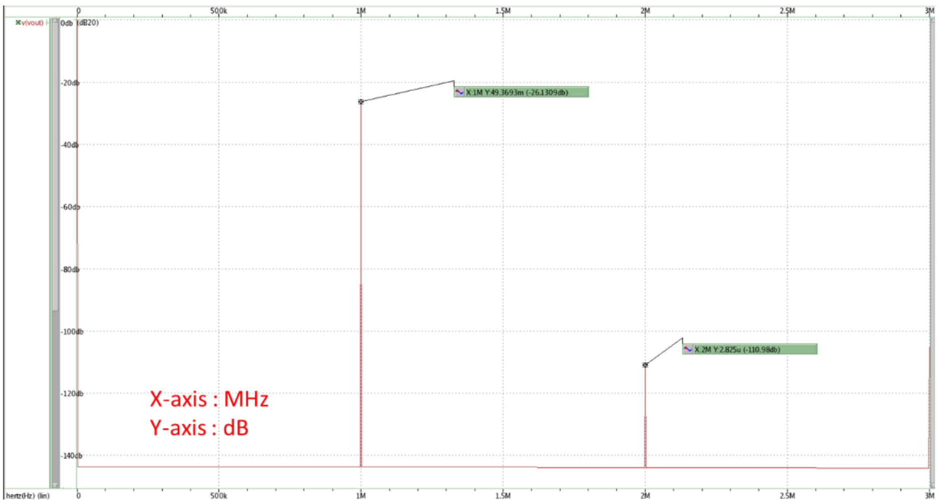
$$\rightarrow \text{with feedback distortion 為 without feedback 的} \frac{1}{R_1^2(1+\beta\alpha_1)^4} \text{倍}$$

$$\beta\alpha_1 = (R_1//R_2) \times \mu_n C_{ox}\frac{W}{L}(V_{in0} - V_{TH}) \times (R_L//R_2) \times \frac{1}{R_2}$$

$$= 818.18 \times 266\mu \times \frac{7779}{180}(0.9 - 0.4926) \times 818.18 \times \frac{1}{9000} = 0.3483$$

$$\frac{1}{R_1^2(1+\beta\alpha_1)^4} = \frac{1}{900^2(1+0.3483)^4} = 3.736 \times 10^{-7}$$

i.



$@1\text{MHz} \rightarrow -26.1309\text{dB}$

$@2\text{MHz} \rightarrow -110.98\text{dB}$

j.

$$\text{THD} = \left(\frac{A_{HD2}}{A_F}\right)^2 = 2[-110.98 - (-26.131)] = -169.698\text{dB}$$

k.

Calculated:

$$\frac{A_{HD2}}{A_F}=\frac{b}{a}=\frac{\alpha_2 V_m}{2R_1}\frac{1}{\alpha_1}\frac{1}{(1+\beta\alpha_1)^2}=\frac{0.025}{2}\frac{1}{3135.102}\frac{1}{(1+0.3483)^2}$$

$$\alpha_2=\frac{1}{2}\times 818.18\times 266\mu\times\frac{7779}{180}\times 818.18=-3847.695$$

$$\frac{A_{HD2}}{A_F}=\frac{3847.695\times 0.025}{2\times 900}\frac{1}{3135.102}\frac{1}{(1+0.3483)^2}=9.377\times 10^{-6}$$

$$\mathrm{THD}=\left(\frac{A_{HD2}}{A_F}\right)^2=2.3535\times 10^{-4}\ \ (\text{without feedback})$$

$$\mathrm{THD}=\left(\frac{A_{HD2}}{A_F}\right)^2=(9.377\times 10^{-6})^2\ \ (\text{with feedback})$$ ∵2)-b 計算過

$$\frac{(9.377\times 10^{-6})^2}{2.3535\times 10^{-4}}=\frac{8.7928\times 10^{-11}}{2.3535\times 10^{-4}}=3.736\times 10^{-7}$$

with feedback distortion 為 without feedback 的 3.736×10^{-7}倍

Simulated:

$$\mathrm{THD}=\left(\frac{A_{HD2}}{A_F}\right)^2=2[-110.98-(-26.131)]=-169.698\mathrm{dB}$$ (with feedback)

$\mathrm{THD}=-122.222\mathrm{dB}$ (without feedback)

$-169.698-(-122.222)=-47.476\mathrm{dB}=4.229\times 10^{-3}$

with feedback distortion 為 without feedback 的 4.229×10^{-3}倍

Compare:

在 THD with feedback 的比較，可發現模擬值較大，推測是因為在計算時省略的部分，或是 I_D 計算時過程時忽略了 channel length modulation 和 body effect 等因素。

在 with feedback 和 without feedback 對線性改善程度比較，模擬的結果改善程度較差，估計是A_{HD2}和A_F的在計算時省略部分參數，以及上述所提到的 I_D 的公式不夠準確造成。