Amp1 & balanced step-up transformer: SN and gain calculations

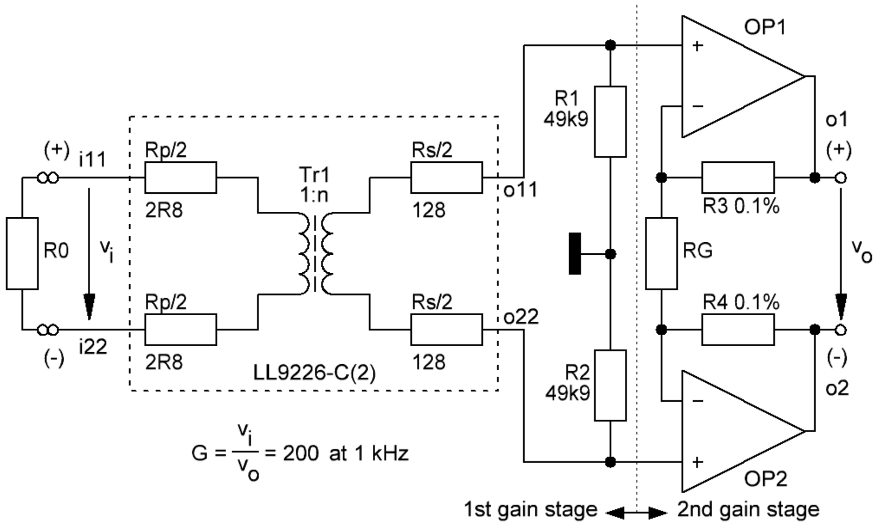

Fig. 1 Warm Amp1 with measured transformer data of LL9226-C(2) & balanced OP37G

Subscripts :

20k = 20Hz ... 20kHz	o1 = output 1	1 = 1 Hz eg B_1 or = simple numbering
c = correlated	cld = cold	i, o = i/p, o/p referred
e = dB with 20log(...)	m = measured	n = noise density in sqrt(1Hz)
N = rms noise voltage in B_{20k}	s = simulated	tot = total
uc = un-correlated	wrm = warm	amp1 = warm Fig. 1

$T := 300.15K$ $\quad k := 1.38065\cdot10^{-23} V\cdot A\cdot s\cdot K^{-1}$ $\quad B_1 := 1Hz$ $\quad TOL := 10^{-18}$

$f := 10Hz, 15Hz .. 100kHz$ $\quad h := 1kHz$ $\quad B_{20k} := 19980Hz$ $\quad v_{i.nom} := 0.5\cdot10^{-3}V$ $\quad v_{o.nom} := 1V$

$R0 := 0\Omega, 0.5\Omega .. 40\Omega$ $\quad Ri := 99.8\cdot10^3\Omega$

1. First gain stage: calculated noise of the warm input network at room temperature :

measured : $\quad G_{1st.m} := 10.961$ $\quad Rp := 5.6\Omega$ $\quad Rs := 258\Omega$

set : $\quad Lp := 780mH$ $\quad$ <= chosen for a flat frequency response in B_{20k}

=> succ-apps of n to get $G_{1st.m}$ in equ. (0) => $\quad n := 11.064634$

$$Zin := \frac{Rs + Ri}{n^2} \qquad Zin = 817.293\,\Omega$$

$$Zin_{tot} := Rp + \frac{Rs + Ri}{n^2} \qquad Zin_{tot} = 822.893\,\Omega$$

$$Zout_{tot}(R0) := Rs + n^2 \cdot (R0 + Rp) \qquad Zout_{tot}(0\Omega) = 943.586\,\Omega$$

$$Gp(R0) := \frac{Zin}{R0 + Zin_{tot}} \qquad Gp(0\Omega) = 0.993$$

$$Gs := \frac{Ri}{Rs + Ri} \qquad Gs = 0.997$$

$$G_{1st.m} := Gs \cdot Gp(0\Omega) \cdot n \qquad G_{1st.m} = 10.961000$$

$$=> \qquad Ls := n^2 \cdot Lp \qquad Ls = 95.492378\,H$$

$$=> \qquad G_{1st}(R0) := Gs \cdot Gp(R0) \cdot n \qquad G_{1st}(0\Omega) = 10.961 \tag{0}$$

$$e_{N.o11.wrm}(R0) := \sqrt{4 \cdot k \cdot T \cdot B_{20k} \cdot \left[(R0 + Rp) \cdot G_{1st}(R0)^2 \ldots \atop + Rs \cdot \left(\frac{Ri}{Zout_{tot}(R0) + Ri} \right)^2 + Ri \cdot \left(\frac{Zout_{tot}(R0)}{Zout_{tot}(R0) + Ri} \right)^2 \right]} \tag{1}$$

$$e_{N.o11.wrm}(0\Omega) = 556.399 \times 10^{-9}\,V$$

Simulation result with R0 = 0Ω => $e_{N.o11.wrm.s} := 556.414 \cdot 10^{-9}\,V$

$$D_{e.wrm}(R0) := 20 \cdot \log\left(\frac{e_{N.o11.wrm}(R0)}{e_{N.o11.wrm.s}} \right) \qquad D_{e.wrm}(0\Omega) = -0.000 \quad [dB]$$

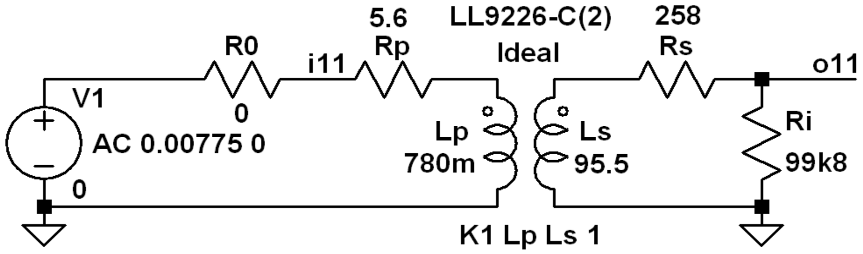

Fig. 2
Simulation schematic of the input network with warm LL9226-C(2) transformer

2. First gain stage: calculated noise of the input network at room temperature, however, with a noiseless = cold (cld) transformer :

$$=> \qquad e_{N.o11.cld}(R0) := \sqrt{4 \cdot k \cdot T \cdot B_{20k} \cdot \left[R0 \cdot G_{1st}(R0)^2 + Ri \cdot \left(\frac{Zout_{tot}(R0)}{Zout_{tot}(R0) + Ri} \right)^2 \right]} \tag{2}$$

$$e_{N.o11.cld}(0\Omega) = 53.848 \times 10^{-9}\,V$$

Simulation result with R0 = 0Ω => $e_{N.o11.cld.s} := 53.8508 \cdot 10^{-9}\,V$

$$D_{e.cld}(R0) := 20 \cdot \log\left(\frac{e_{N.o11.cld}(R0)}{e_{N.o11.cld.s}}\right) \qquad D_{e.cld}(0\Omega) = -0.000 \quad \text{[dB]}$$

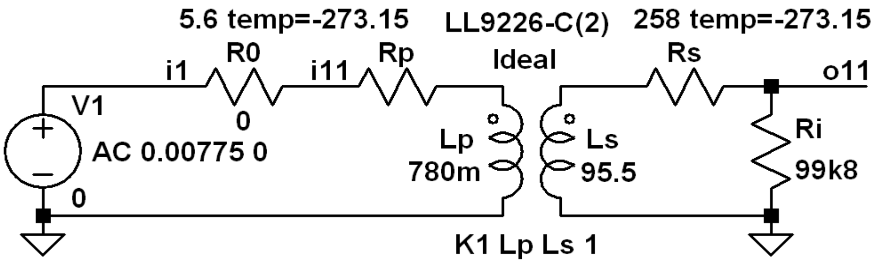

Fig. 3
Simulation schematic of the input network with cold LL9226-C(2) transformer

3. First gain stage: deltas between the warm and cold situation = Worsening effect W of the cold transformer vs. the warm one :

$$W_{e.o}(R0) := 20 \cdot \log\left(\frac{e_{N.o11.cld}(R0)}{e_{N.o11.wrm}(R0)}\right) \qquad W_{e.o}(0\Omega) = -20.284 \quad \text{[dB]} \qquad (3)$$

$$W_{e.o}(10\Omega) = -2.411 \quad \text{[dB]}$$

$$W_{e.s} := 20 \cdot \log\left(\frac{e_{N.o11.cld.s}}{e_{N.o11.wrm.s}}\right) \qquad W_{e.s} = -20.284 \quad \text{[dB]}$$

$$W_{e.s.10} := -2.411 \quad \text{[dB]}$$

$$W_{e.o}(0\Omega) - W_{e.s} = -0.000 \quad \text{[dB]}$$

$$W_{e.o}(10\Omega) - W_{e.s.10} = 0.000 \quad \text{[dB]}$$

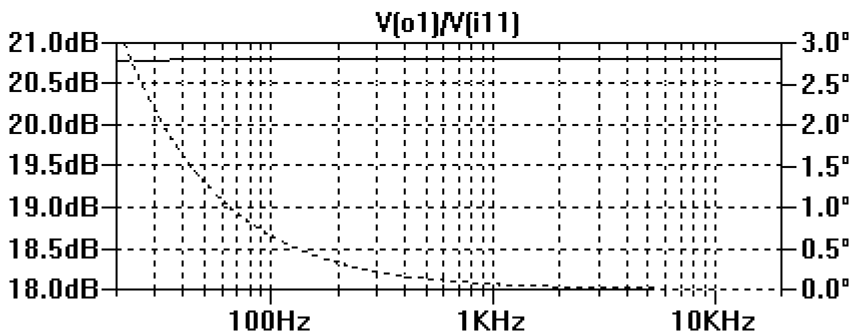

Fig. 4
F (solid) & P (dotted) responses of Figs. 2 & 3

4. First gain stage: graphs :

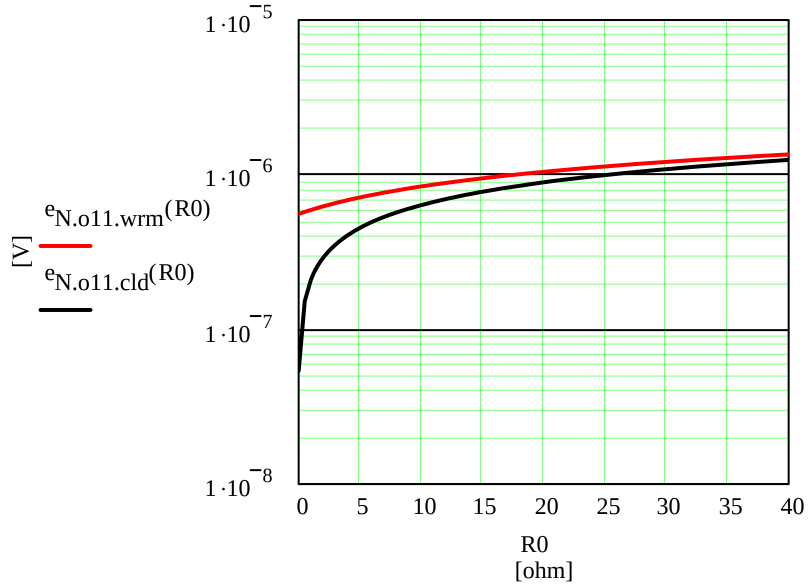

Fig. 5
R0-dependent warm (red) and cold (blk) rms output noise voltages, (1) & (2)

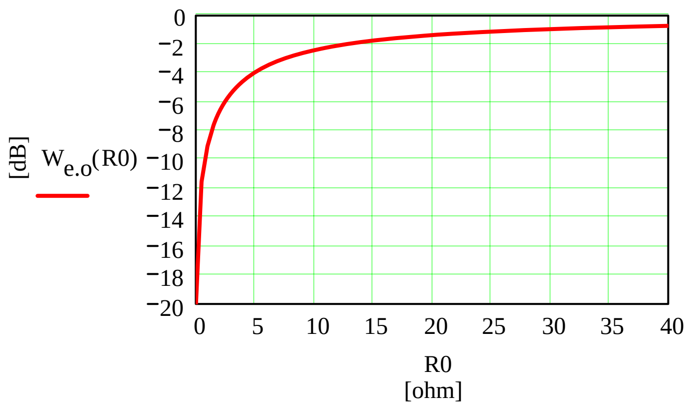

Fig. 6
Trace of equ. (3): Worsening of the cold transformer vs. R0

5. Second gain stage: gain and component data as of Fig. 1 :

$R1 := 49.9\cdot10^{3}\Omega$ $\quad R2 := R1$ $\quad R4 := 1\cdot10^{3}\Omega$ $\quad R5 := R4$

$G_{tot} := 200$ $\quad G_{2nd} := \dfrac{G_{tot}}{G_{1st}(0\Omega)}$ $\quad G_{2nd} = 18.247$

$G_{2nd} = 1 + \dfrac{R4 + R5}{RG}$ $\quad RG := \dfrac{R4 + R5}{G_{2nd} - 1}$ $\quad RG = 115.965\,\Omega$

6. Amp1 complete: calculation of the noise voltages :

Note: OP37 & OP27 have 100% correlated input referred current noise sources !
Voltage & current noise data taken from AD's datasheet

6.1 Relevant resistance data from the 1st gain stage :

$R0_{sec}(R0) := R0 \cdot n^2$ $\qquad R0_{sec}(0\Omega) = 0.000\,\Omega$

$Rp_{sec} := Rp \cdot n^2$ $\qquad Rp_{sec} = 685.586\,\Omega$

$Z_{tr1}(R0) := R0_{sec}(R0) + Rp_{sec} + Rs$ $\qquad Z_{tr1}(0\Omega) = 943.586\,\Omega$

6.2 Relevant noise data of the op-amps :

$e_{n.i1} := 3.2 \cdot 10^{-9} V$ $\qquad f_{c.e1} := 2.7Hz$ $\qquad i_{n.i1} := 0.4 \cdot 10^{-12} A$ $\qquad f_{c.i1} := 120Hz$

$e_{n.i2} := e_{n.i1}$ $\qquad i_{n.i2} := i_{n.i1}$

$$e_{n.i1}(f) := e_{n.i1} \cdot \sqrt{\left(\frac{f}{f_{c.e1}}\right)^{-1} + 1} \qquad i_{n.i1}(f) := i_{n.i1} \cdot \sqrt{\left(\frac{f}{f_{c.i1}}\right)^{-1} + 1}$$

$e_{n.i2}(f) := e_{n.i1}(f)$ $\qquad i_{n.i2}(f) := i_{n.i1}(f)$

6.3 Relevant resistance data and corresponding noise after Delta-Y-transformation of the balanced version of Fig. 2 :

$$Ry(R0) := \frac{R1^2}{Z_{tr1}(R0) + 2 \cdot R1} \qquad Ry(0\Omega) = 24.716 \times 10^3\,\Omega$$

$$Rx(R0) := \frac{Z_{tr1}(R0) \cdot R1}{Z_{tr1}(R0) + 2 \cdot R1} \qquad Rx(0\Omega) = 467.374 \times 10^0\,\Omega$$

$$i_{n.i}(f) := \sqrt{i_{n.i1}(f)^2 + i_{n.i2}(f)^2} \qquad i_{n.i}(h) = 598.665 \times 10^{-15} A$$

$$e_{n.Rx}(R0) := \sqrt{4 \cdot k \cdot T \cdot B_1 \cdot Rx(R0)} \qquad e_{n.Rx}(0\Omega) = 2.783 \times 10^{-9} V$$

$$e_{n.Ry}(R0) := \sqrt{4 \cdot k \cdot T \cdot B_1 \cdot Ry(R0)} \qquad e_{n.Ry}(0\Omega) = 20.241 \times 10^{-9} V$$

$$e_{n.Ry.tot}(f, R0) := \sqrt{e_{n.Ry}(R0)^2 + i_{n.i}(f)^2 \cdot Ry(R0)^2} \qquad e_{n.Ry.tot}(h, 0\Omega) = 25.073 \times 10^{-9} V$$

$$e_{n.RG} := \sqrt{4 \cdot k \cdot T \cdot B_1 \cdot RG} \qquad e_{n.RG} = 1.386 \times 10^{-9} V$$

$$e_{n.R4} := \sqrt{4 \cdot k \cdot T \cdot B_1 \cdot R4} \qquad e_{n.R4} = 4.071 \times 10^{-9} V$$

6.4 Noise voltage at the output of the warm Amp1 :

6.4.1 Noise voltages between the output leads (= balanced output) :

$Gx := 0.5 + \frac{R4}{RG}$ $\quad Gx = 9.123 \quad$ $Gy := \frac{R4}{RG}$ $\quad Gy = 8.623$

$$e_{n.o1.c}(f,R0) := \sqrt{2\cdot\left(e_{n.i1}(f)^2 + e_{n.Rx}(R0)^2 + i_{n.i1}(f)^2\cdot Rx(R0)^2\right)\cdot Gx^2 + e_{n.RG}{}^2\cdot Gy^2} \qquad (4)$$

$e_{n.o1.c}(h,0\Omega) = 56.110\times 10^{-9}\,V$

$e_{n.o2.c}(f,R0) := e_{n.o1.c}(f,R0)$

$e_{n.o1.uc}(f) := \sqrt{e_{n.R4}{}^2 + i_{n.i1}(f)^2\cdot R4^2}$ $\qquad e_{n.o1.uc}(h) = 4.093\times 10^{-9}\,V$

$e_{n.o2.uc}(f) := e_{n.o1.uc}(f)$

6.4.2 Amp1's input and output referred noise voltage densities and SNs :

$e_{n.o.amp1}(f,R0) := \sqrt{4\cdot e_{n.o1.c}(f,R0)^2 + 2\cdot e_{n.o1.uc}(f)^2}$ $\qquad e_{n.o.amp1}(h,0\Omega) = 112.370\times 10^{-9}\,V$

Plus correlated current noise of the op-amps taken into account :

$$e_{n.o.amp1}(f,R0) := \sqrt{8\, e_{n.i1}(f)^2\cdot Gx^2 + 8\cdot e_{n.Rx}(R0)^2\cdot Gx^2 + 4\cdot e_{n.RG}{}^2\cdot Gy^2 + 2\cdot e_{n.R4}{}^2 \ldots + i_{n.i1}(f)^2\cdot\left(\sqrt{8}\cdot Rx(R0)\cdot Gx + 2\cdot R4\right)^2} \qquad (5)$$

$e_{n.o.amp1}(h,0\Omega) = 112.410\times 10^{-9}\,V$

$e_{n.i.amp1}(f,R0) := \frac{e_{n.o.amp1}(f,R0)}{G_{tot}}$ $\qquad e_{n.i.amp1}(h,0\Omega) = 562.048\times 10^{-12}\,V$

$e_{N.i.amp1}(R0) := \sqrt{\frac{1}{B_1}\cdot\int_{20Hz}^{20000Hz}\left(\left|e_{n.i.amp1}(f,R0)\right|\right)^2 df}$ $\qquad e_{N.i.amp1}(0\Omega) = 79.400\times 10^{-9}\,V$

$e_{N.o.amp1}(R0) := \sqrt{\frac{1}{B_1}\cdot\int_{20Hz}^{20000Hz}\left(\left|e_{n.o.amp1}(f,R0)\right|\right)^2 df}$ $\qquad e_{N.o.amp1}(0\Omega) = 15.880\times 10^{-6}\,V$

$SN_{o.amp1}(R0) := 20\cdot\log\left(\frac{e_{N.o.amp1}(R0)}{v_{o.nom}}\right)$ $\qquad SN_{o.amp1}(0\Omega) = -95.983$ [dBV]

Simulation result with R0 = 0Ω => $SN_{o.amp1.s} := -95.987$ [dBV]

$SN_{o.amp1}(0\Omega) - SN_{o.amp1.s} = 0.004$ [dB]

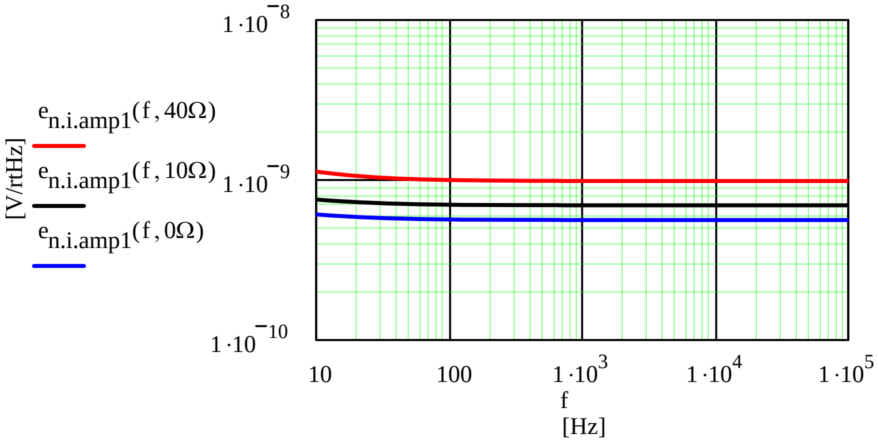

Fig. 7
Amp1's R0-dependent input noise voltage densities vs. frequency for R0 = 0Ω, 10Ω, and 40Ω à la equ. (5)

7. Rough calculation: Amp1's input and output referred noise voltage densities and SNs - cold version of LL9226-C(2) :

$e_{n.Rs} := \sqrt{4\cdot k\cdot T\cdot B_1\cdot Rs}$ $\qquad e_{n.Rs} = 2.068\times10^{-9}\,V$

$e_{n.Rp} := \sqrt{4\cdot k\cdot T\cdot B_1\cdot Rp}$ $\qquad e_{n.Rp} = 304.674\times10^{-12}\,V$

$e_{n.Rp.sec} := \sqrt{4\cdot k\cdot T\cdot B_1\cdot Rp_{sec}}$ $\qquad e_{n.Rp.sec} = 3.371\times10^{-9}\,V$

$$e_{n.o.cld}(f, R0) := \sqrt{e_{n.o.amp1}(f, R0)^2 - \left(e_{n.Rs}{}^2 + e_{n.Rp.sec}{}^2\right)\cdot G_{2nd}{}^2\cdot Gs^2\cdot Gp(R0)^2} \qquad (6)$$

$e_{n.o.cld}(h, 0\Omega) = 86.750\times10^{-9}\,V$

$e_{n.i.cld}(f, R0) := e_{n.o.cld}(f, R0)\cdot G_{tot}{}^{-1}$ $\qquad e_{n.i.cld}(h, 0\Omega) = 433.750\times10^{-12}\,V$

$$e_{N.o.cld}(R0) := \sqrt{\frac{1}{B_1}\cdot\int_{20Hz}^{20000Hz}\left(\left|e_{n.o.cld}(f, R0)\right|\right)^2 df} \qquad e_{N.o.cld}(0\Omega) = 12.250\times10^{-6}\,V$$

$$e_{N.i.cld}(R0) := \sqrt{\frac{1}{B_1}\cdot\int_{20Hz}^{20000Hz}\left(\left|e_{n.i.cld}(f, R0)\right|\right)^2 df} \qquad e_{N.i.cld}(0\Omega) = 61.252\times10^{-9}\,V$$

$$SN_{i.cld}(R0) := 20\cdot\log\left(\frac{e_{N.i.cld}(R0)}{v_{i.nom}}\right) \qquad SN_{i.cld}(0\Omega) = -78.237 \quad [dB]$$

$$SN_{o.cld}(R0) := 20\cdot\log\left(\frac{e_{N.o.cld}(R0)}{v_{o.nom}}\right) \qquad SN_{o.cld}(0\Omega) = -98.237 \quad [dBV]$$

Simulation result with R0 = 0Ω => $SN_{o.cld.s} := -98.242$ [dBV]

$SN_{o.cld}(0\Omega) - SN_{o.cld.s} = 0.005$ [dB]

8. Amp1's 2nd gain stage with input shorted to ground: output referred noise voltage densities and SNs :

$Rs := 0\Omega$ $Rp := 0\Omega$ $R1 := 0\Omega$ $R2 := 0\Omega$

$$e_{n.o.2nd}(f) := \sqrt{8 \cdot e_{n.i1}(f)^2 \cdot Gx^2 + 4 \cdot e_{n.RG}{}^2 \cdot Gy^2 + 2 \cdot e_{n.R4}{}^2 + 4 \cdot i_{n.i1}(f)^2 \cdot R4^2} \qquad (7)$$

$e_{n.o.2nd}(h) = 86.270 \times 10^{-9}\,V$

$$e_{n.i.2nd}(f) := \frac{e_{n.o.2nd}(f)}{G_{tot}}$$

$e_{n.i.2nd}(h) = 431.351 \times 10^{-12}\,V$

$$e_{N.o.2nd} := \sqrt{\frac{1}{B_1} \cdot \int_{20Hz}^{20000Hz} \left(\left|e_{n.o.2nd}(f)\right|\right)^2 df}$$

$e_{N.o.2nd} = 12.184 \times 10^{-6}\,V$

$$SN_{o.2nd} := 20 \cdot \log\left(\frac{e_{N.o.2nd}}{v_{o.nom}}\right)$$

$SN_{o.2nd} = -98.284$ [dBV]

Simulation result with R0 = 0Ω => $SN_{o.2nd.s} := -98.291$ [dBV]

$SN_{o.2nd} - SN_{o.2nd.s} = 0.007$ [dB]

9. Current noise inmpact CNI :

$CNI := SN_{o.cld}(0\Omega) - SN_{o.2nd}$ $CNI = 0.047$ [dB]

10. Amp1 graphs :

$SN_{o.wrm}(R0) := SN_{o.amp1}(R0)$

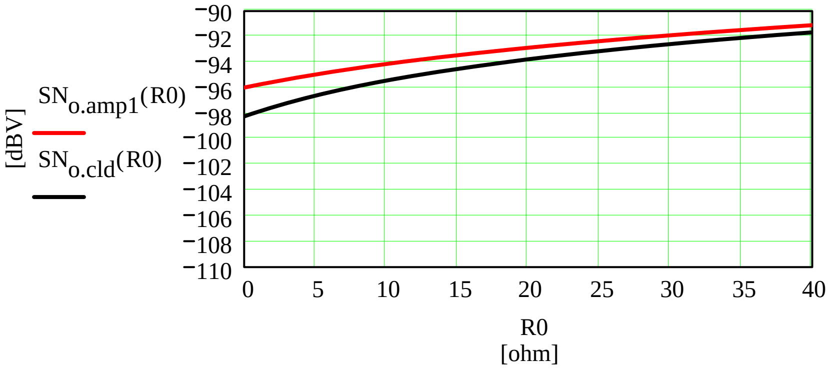

Fig. 8
Traces of the R0-dependent SNs of the warm Amp vs. the cold one, derived from equ. (4) & (6)

Worsening W of the output referred SN of the warm Amp1versus the cold one :

$$W_o(R0) := SN_{o.cld}(R0) - SN_{o.amp1}(R0) \qquad (8)$$

$W_o(10\Omega) = -1.300$ [dB]

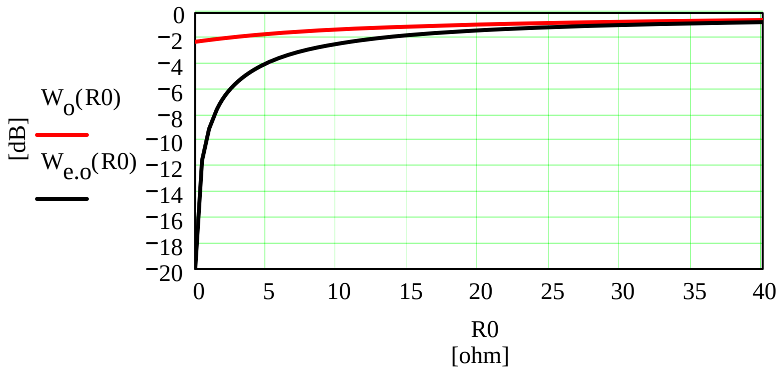

Fig. 9
Trace of the R0-dependent SN worsening W of the cold Amp vs. the warm one, equ. (8) (red) plus trace of Fig. 6 trafo alone equ. (3) (blk)

11. Input referred RIAA equalized & A-weighted SNs :

$$A(f) := \frac{1.259}{1+\left(\frac{20.6\text{Hz}}{f}\right)^2}\cdot\frac{1}{\sqrt{1+\left(\frac{107.7\text{Hz}}{f}\right)^2}}\cdot\frac{1}{\sqrt{1+\left(\frac{737.9\text{Hz}}{f}\right)^2}}\cdot\frac{1}{1+\left(\frac{f}{12200\text{Hz}}\right)^2}$$

$$R_{1kHz} := \frac{\sqrt{1+\left(2\cdot\pi\cdot 1\text{kHz}\cdot 318\cdot 10^{-6}\text{s}\right)^2}}{\sqrt{1+\left(2\cdot\pi\cdot 1\text{kHz}\cdot 3180\cdot 10^{-6}\text{s}\right)^2}\cdot\sqrt{1+\left(2\cdot\pi\cdot 1\text{kHz}\cdot 75\cdot 10^{-6}\text{s}\right)^2}} \qquad R_{1kHz} = 101.030\times 10^{-3}$$

$$R(f) := \frac{\sqrt{1+\left(2\cdot\pi\cdot f\cdot 318\cdot 10^{-6}\text{s}\right)^2}}{\sqrt{1+\left(2\cdot\pi\cdot f\cdot 3180\cdot 10^{-6}\text{s}\right)^2}\cdot\sqrt{1+\left(2\cdot\pi\cdot f\cdot 75\cdot 10^{-6}\text{s}\right)^2}}\cdot R_{1kHz}^{-1} \qquad R(1\text{kHz}) = 1.000$$

$$SN_{wrm.ariaa.i}(R0) := 20\cdot\log\left[\frac{\sqrt{\frac{1}{B_1}\cdot\int_{20\text{Hz}}^{20000\text{Hz}}\left(\left|e_{n.i.amp1}(f,R0)\right|\right)^2\cdot\left(\left|A(f)\right|\right)^2\cdot\left(\left|R(f)\right|\right)^2\,df}}{v_{i.nom}}\right] \qquad (9)$$

$$SN_{cld.ariaa.i}(R0) := 20\cdot\log\left[\frac{\sqrt{\frac{1}{B_1}\cdot\int_{20\text{Hz}}^{20000\text{Hz}}\left(\left|e_{n.i.cld}(f,R0)\right|\right)^2\cdot\left(\left|A(f)\right|\right)^2\cdot\left(\left|R(f)\right|\right)^2\,df}}{v_{i.nom}}\right] \qquad (10)$$

Simulation result with R0 = 0Ω => $SN_{wrm.ariaa.i.s} := -83.916$ $\quad SN_{wrm.ariaa.i}(0\Omega) = -83.914$ [dB(A)]

Simulation result with R0 = 10Ω => $SN_{wrm.ariaa.i.s} := -82.075$ $\quad SN_{wrm.ariaa.i}(10\Omega) = -82.073$ [dB(A)]

Simulation result with R0 = 40Ω => $SN_{wrm.ariaa.i.s} := -79.038$ $\quad SN_{wrm.ariaa.i}(40\Omega) = -79.036$ [dB(A)]

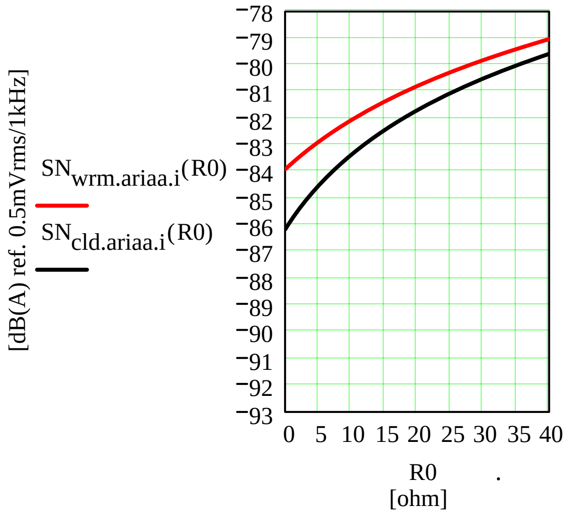

Fig. 10
Trace of the
R0-dependent
input referred
SNs. (9) & (10)

12. Noise of the transformer with R0 = 0Ω and after special treatments :

$f := 20\text{Hz}, 25\text{Hz} .. 20\text{kHz}$

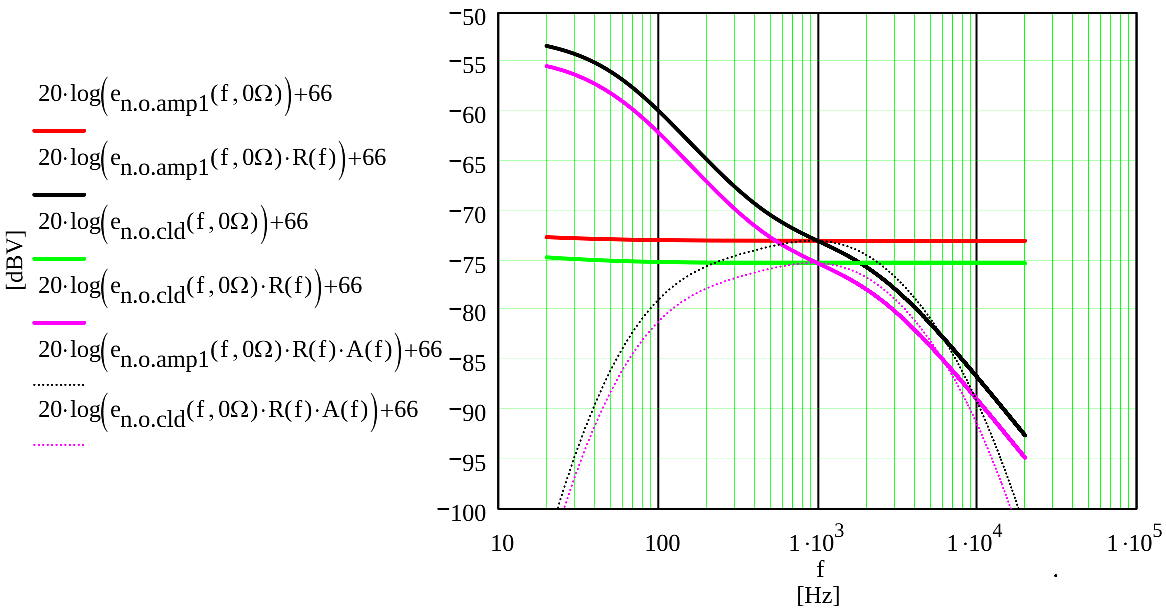

Fig. 12 Curves of the transformer noise after special treatments

Worsening = Delta red minus green at 1 kHz:

$$W_e(f, R0) := 20 \cdot \log\left(\frac{e_{n.o.amp1}(f, R0)}{e_{n.o.cld}(f, R0)}\right)$$

$W_e(h, 0\Omega) = 2.251$ [dB]