Amp with unbalanced step-up transformer: SN and gain calculations

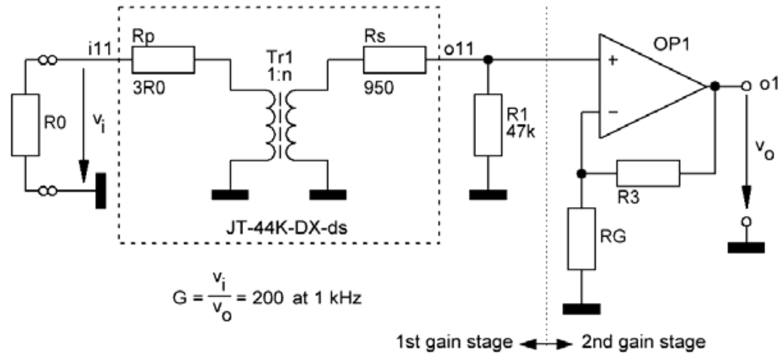

Fig. 1 Amp with warm transformer and data of JT-44K-DX-ds' datasheet & OP37G

Subscripts :

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

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

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

0. Relevant transformer data :

$Rp := 3.0\Omega$ $\quad Rs := 950\Omega$ $\quad R0 := 0\Omega, 0.5\Omega .. 40\Omega$ $\quad Ri := 47\cdot10^3\Omega$

$Lp := 1.3H$ $\quad Ls := 130H$ $\quad$ <= chosen for a flat frequency response in B_{20k} $\quad n := \sqrt{\frac{Ls}{Lp}}$ $\quad n = 10.000$

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

$$Zin := \frac{Rs + Ri}{n^2} \qquad Zin = 479.500\,\Omega$$

$$Zin_{tot} := Rp + \frac{Rs + Ri}{n^2} \qquad Zin_{tot} = 482.500\,\Omega$$

$$Zout_{tot}(R0) := Rs + n^2\cdot(R0 + Rp) \qquad Zout_{tot}(0\Omega) = 1250.000\,\Omega$$

$$Gp(R0) := \frac{Zin}{R0 + Zin_{tot}} \qquad Gp(0\Omega) = 0.994$$

$$Gs := \frac{Ri}{Rs + Ri} \qquad Gs = 0.980$$

$$G1(R0) := Gs\cdot Gp(R0)\cdot n \qquad G_{1st} := G1(0\Omega) \qquad G_{1st} = 9.740933$$

$$e_{N.o11.wrm}(R0) := \sqrt{4\cdot k\cdot T\cdot B_{20k}\cdot\left[(R0+Rp)\cdot G1(R0)^2 \ldots + Rs\cdot\left(\frac{Ri}{Zout_{tot}(R0)+Ri}\right)^2 + Ri\cdot\left(\frac{Zout_{tot}(R0)}{Zout_{tot}(R0)+Ri}\right)^2\right]} \qquad (1)$$

$e_{N.o11.wrm}(0\Omega) = 635.030 \times 10^{-9}\,V$

Simulation result with R0 = 0Ω => $e_{N.o11.wrm.s} := 635.030\cdot 10^{-9}V$

$$D_{e.wrm}(R0) := 20\cdot\log\left(\frac{e_{N.o11.wrm}(R0)}{e_{N.o11.wrm.s}}\right)$$

$D_{e.wrm}(0\Omega) = -0.000$ [dB]

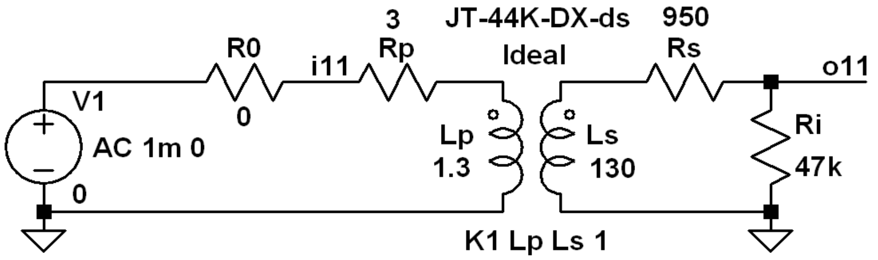

Fig. 2
Simulation schematic of the input network with warm JT-44K-DX-ds transformer

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

$$=> \quad e_{N.o11.cld}(R0) := \sqrt{4\cdot k\cdot T\cdot B_{20k}\cdot\left[R0\cdot G1(R0)^2 + Ri\cdot\left(\frac{Zout_{tot}(R0)}{Zout_{tot}(R0)+Ri}\right)^2\right]} \qquad (2)$$

$e_{N.o11.cld}(0\Omega) = 102.212 \times 10^{-9}\,V$

Simulation result with R0 = 0Ω => $e_{N.o11.cld.s} := 102.212\cdot 10^{-9}V$

$$D_{e.cld}(R0) := 20\cdot\log\left(\frac{e_{N.o11.cld}(R0)}{e_{N.o11.cld.s}}\right)$$

$D_{e.cld}(0\Omega) = -0.000$ [dB]

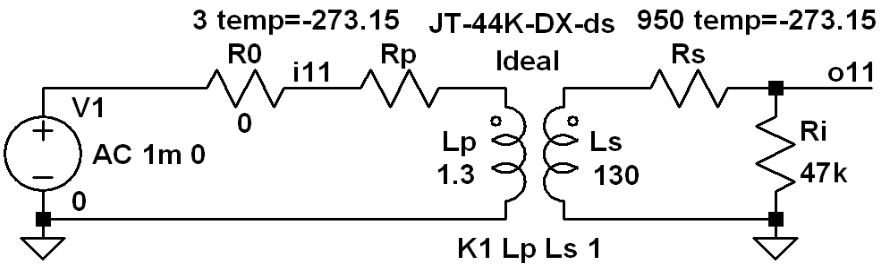

Fig. 3
Simulation schematic of the input network with cold JT-44K-DX-ds transformer

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

$$W_{e.o}(R0) := 20\cdot\log\left(\frac{e_{N.o11.cld}(R0)}{e_{N.o11.wrm}(R0)}\right) \qquad W_{e.o}(0\Omega) = -15.866 \quad \text{[dB]} \qquad (3)$$

$$W_{e.o}(10\Omega) = -3.281 \quad \text{[dB]}$$

$$W_{e.s} := 20\cdot\log\left(\frac{e_{N.o11.cld.s}}{e_{N.o11.wrm.s}}\right) \qquad W_{e.s} = -15.866 \quad \text{[dB]}$$

$$W_{e.s.10} := -3.281 \quad \text{[dB]}$$

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

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

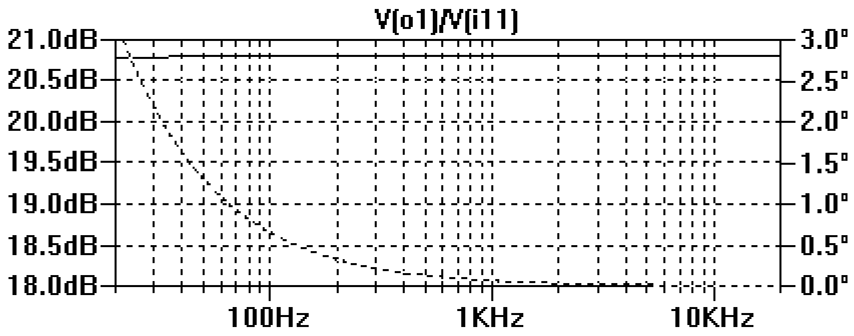

Fig. 4
F (solid) & P (dotted) responses of Figs. 2 & 3

4. First gain stage: graphs :

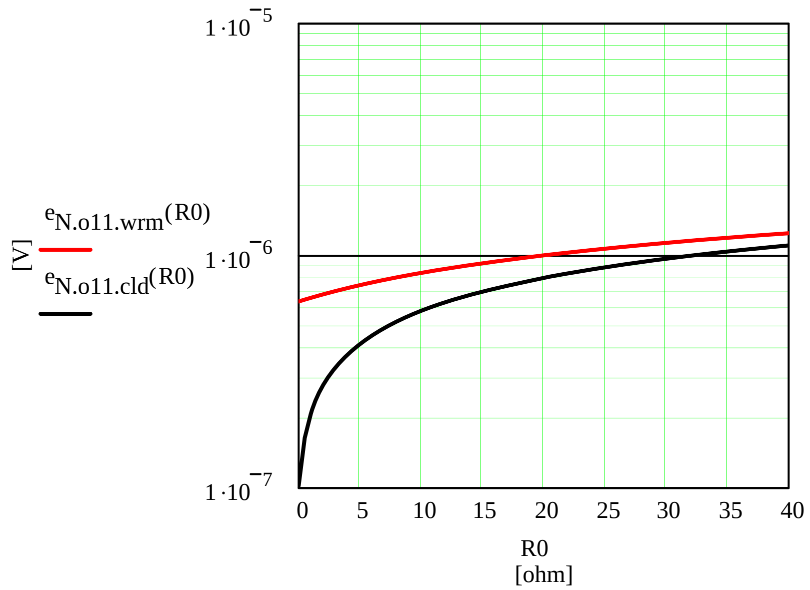

Fig. 5
R0-dependent warm (red) and cold (blk) rms output noise voltages, (1) & (2)

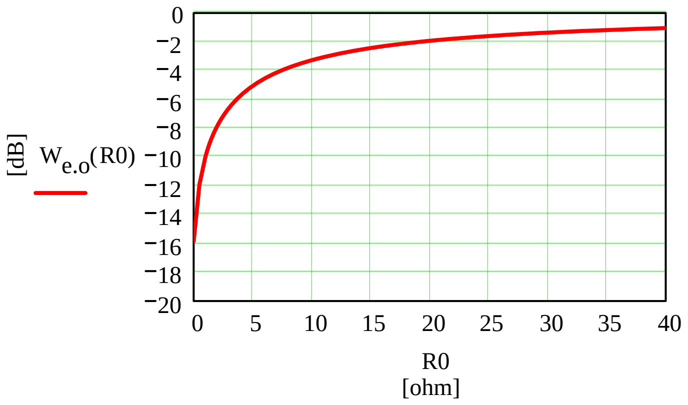

Fig. 6
Trace of equ. (3):
Worsening of the
cold transformer
vs. R0

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

$R1 := 47 \cdot 10^{3} \Omega$ $\qquad R1 = Ri$ $\qquad R3 := 1 \cdot 10^{3} \Omega$

$G_{tot} := 200$ $\qquad G_{2nd} := \dfrac{G_{tot}}{G_{1st}}$ $\qquad G_{2nd} = 20.532$

$G_{2nd} = 1 + \dfrac{R3}{RG}$ $\qquad RG := \dfrac{R3}{G_{2nd} - 1}$ $\qquad RG = 51.198\,\Omega$

6. Amp complete: calculation of the noise voltages :

Note: OP27 & OP37 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 :

$$Z_{i.tot}(R0) := \frac{Zout_{tot}(R0) \cdot R1}{Zout_{tot}(R0) + R1} \qquad Z_{i.tot}(0\Omega) = 1.218 \times 10^{3}\,\Omega$$

6.2 Relevant noise data of the op-amps :

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

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

6.3 Relevant resistance data and corresponding noise :

$$Rf := \frac{RG \cdot R3}{RG + R3} \qquad Rf = 48.705\,\Omega$$

$$e_{n.Rf} := \sqrt{4 \cdot k \cdot T \cdot B_1 \cdot Rf} \qquad e_{n.Rf} = 898.517 \times 10^{-12}\,V$$

6.4 Noise voltage at the output of the warm Amp :

$$e_{n.o11.wrm}(R0) := e_{N.o11.wrm}(R0) \cdot \sqrt{\frac{B_1}{B_{20k}}} \qquad e_{n.o11.wrm}(0\Omega) = 4.493 \times 10^{-9}\,V$$

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

$$e_{n.o.wrm}(f, R0) := G_{2nd} \cdot \sqrt{e_{n.i1}(f)^2 + e_{n.Rf}{}^2 + i_{n.i1}(f)^2 \cdot \left(Rf + Z_{i.tot}(R0)\right)^2 + e_{n.o11.wrm}(R0)^2} \qquad (4)$$

$$e_{n.o.wrm}(h, 0\Omega) = 115.319 \times 10^{-9}\,V$$

$$e_{n.i.wrm}(f, R0) := \frac{e_{n.o.wrm}(f, R0)}{G_{tot}} \qquad e_{n.i.wrm}(h, 0\Omega) = 576.593 \times 10^{-12}\,V \qquad (5)$$

$$e_{N.i.wrm}(R0) := \sqrt{\frac{1}{B_1} \cdot \int_{20Hz}^{20000Hz} \left(\left|e_{n.i.wrm}(f, R0)\right|\right)^2 df} \qquad e_{N.i.wrm}(0\Omega) = 81.452 \times 10^{-9}\,V$$

$$e_{N.o.wrm}(R0) := \sqrt{\frac{1}{B_1} \cdot \int_{20Hz}^{20000Hz} \left(\left|e_{n.o.wrm}(f, R0)\right|\right)^2 df} \qquad e_{N.o.wrm}(0\Omega) = 16.290 \times 10^{-6}\,V$$

$$SN_{o.wrm}(R0) := 20 \cdot \log\left(\frac{e_{N.o.wrm}(R0)}{v_{o.nom}}\right) \qquad SN_{o.wrm}(0\Omega) = -95.761 \quad [dBV]$$

Simulation result with R0 = 0Ω => $SN_{o.wrm.s} := -95.761$ [dBV]

$$SN_{o.wrm}(0\Omega) - SN_{o.wrm.s} = -0.000 \quad [dB]$$

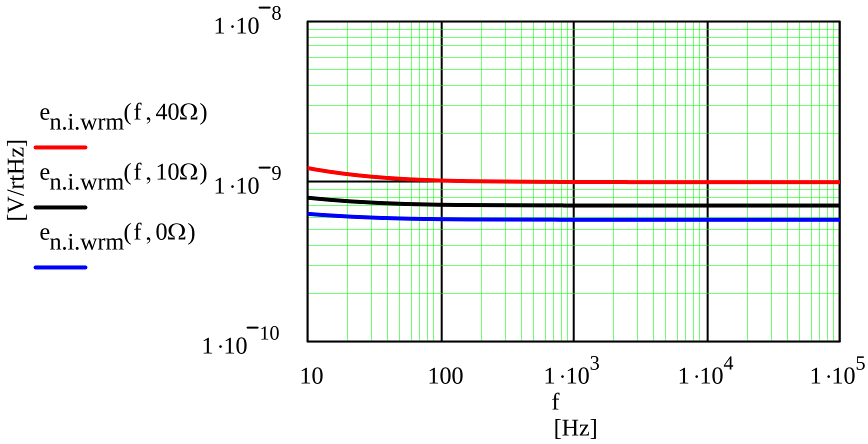

Fig. 7
Amp's
R0-dependent
input noise voltage
densities vs.
frequency for R0 =
0Ω, 10Ω, and 40Ω
à la equ. (4)

7. Calculation: Amp's input and output referred noise voltage densities and SNs - cold version of JT-44K-DX-ds :

$e_{n.Rs} := \sqrt{4 \cdot k \cdot T \cdot B_1 \cdot Rs}$ $\qquad e_{n.Rs} = 3.968 \times 10^{-9}\,V$

$Rp_{sec} := n^2 \cdot Rp$ $\qquad Rp_{sec} = 300.000\,\Omega$

$e_{n.Rp.sec} := \sqrt{4 \cdot k \cdot T \cdot B_1 \cdot Rp_{sec}}$ $\qquad e_{n.Rp.sec} = 2.230 \times 10^{-9}\,V$

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

$e_{n.o.cld}(h, 0\Omega) = 70.784 \times 10^{-9}\,V$

$$e_{n.i.cld}(f, R0) := e_{n.o.cld}(f, R0) \cdot G_{tot}{}^{-1} \qquad e_{n.i.cld}(h, 0\Omega) = 353.918 \times 10^{-12}\,V \qquad (7)$$

$$e_{N.o.cld}(R0) := \sqrt{\frac{1}{B_1} \cdot \int_{20Hz}^{20000Hz} \left(\left|e_{n.o.cld}(f, R0)\right|\right)^2 df} \qquad e_{N.o.cld}(0\Omega) = 9.989 \times 10^{-6}\,V$$

$$e_{N.i.cld}(R0) := \sqrt{\frac{1}{B_1} \cdot \int_{20Hz}^{20000Hz} \left(\left|e_{n.i.cld}(f, R0)\right|\right)^2 df} \qquad e_{N.i.cld}(0\Omega) = 49.946 \times 10^{-9}\,V$$

$$SN_{i.cld}(R0) := 20 \cdot \log\left(\frac{e_{N.i.cld}(R0)}{v_{i.nom}}\right) \qquad SN_{i.cld}(0\Omega) = -80.009 \quad [dB]$$

$$SN_{o.cld}(R0) := 20 \cdot \log\left(\frac{e_{N.o.cld}(R0)}{v_{o.nom}}\right) \qquad SN_{o.cld}(0\Omega) = -100.009 \quad [dBV]$$

Simulation result with R0 = 0Ω => $SN_{o.cld.s} := -100.009$ [dBV]

$SN_{o.cld}(0\Omega) - SN_{o.cld.s} = -0.000$ [dB]

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

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

$$e_{n.o.2nd}(f) := G_{2nd}\cdot\sqrt{e_{n.i1}(f)^2 + e_{n.Rf}{}^2 + i_{n.i1}(f)^2\cdot Rf^2}$$ $$e_{n.o.2nd}(h) = 68.330\times 10^{-9}\,V$$

$$e_{N.o.2nd} := \sqrt{\frac{1}{B_1}\cdot\int_{20Hz}^{20000Hz}\left(\left|e_{n.o.2nd}(f)\right|\right)^2 df}$$ $$e_{N.o.2nd} = 9.651\times 10^{-6}\,V$$

$$SN_{o.2nd} := 20\cdot\log\left(\frac{e_{N.o.2nd}}{v_{o.nom}}\right)$$ $$SN_{o.2nd} = -100.309 \quad [dBV]$$

Simulation result with R0 = 0Ω => $SN_{o.2nd.s} := -100.309$ [dBV]

$SN_{o.2nd} - SN_{o.2nd.s} = 0.000$ [dB]

9. Current noise inmpact CNI at R0 = 0R0 :

$$CNI := SN_{o.cld}(0\Omega) - SN_{o.2nd}$$ $$CNI = 0.300 \quad [dB]$$

10. Amp graphs :

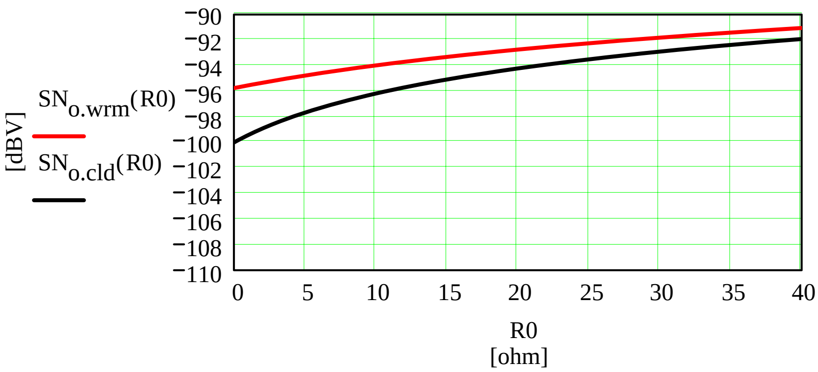

Fig. 8
Traces of the R0-dependent SNs of the warm Amp vs. the cold one, derived from equ. (4) & (6)

Worsening W of the output referred SN of the warm Amp versus the cold one :

$$W_o(R0) := SN_{o.cld}(R0) - SN_{o.wrm}(R0)$$ $$W_o(10\Omega) = -2.202 \quad [dB] \quad (8)$$

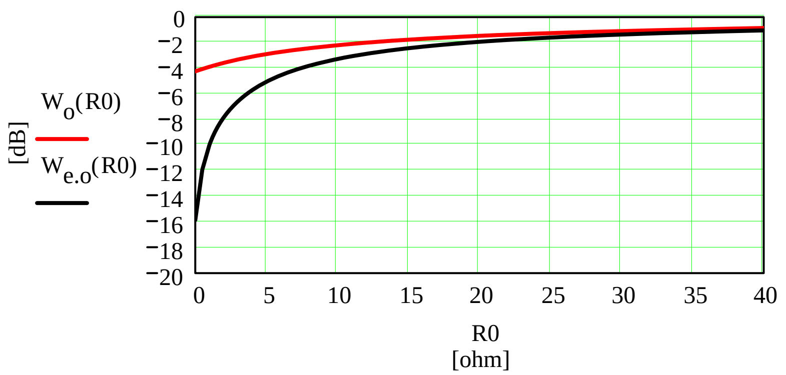

Fig. 9
Trace of the R0-dependent SN worsening W of the cold Amp vs. the warm one, equ. (8) (red) plus trace of Fig. 6 trafo alone equ. (3) (blk)

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

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

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

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

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

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

Simulation result with R0 = 0Ω => $SN_{wrm.ariaa.i.s.0} := -83.692$ $\quad SN_{wrm.ariaa.i}(0\Omega) = -83.692$ [dB(A)]

Simulation result with R0 = 10Ω => $SN_{wrm.ariaa.i.s.10} := -81.911$ $\quad SN_{wrm.ariaa.i}(10\Omega) = -81.912$ [dB(A)]

Simulation result with R0 = 40Ω => $SN_{wrm.ariaa.i.s.40} := -78.976$ $\quad SN_{wrm.ariaa.i}(40\Omega) = -78.978$ [dB(A)]

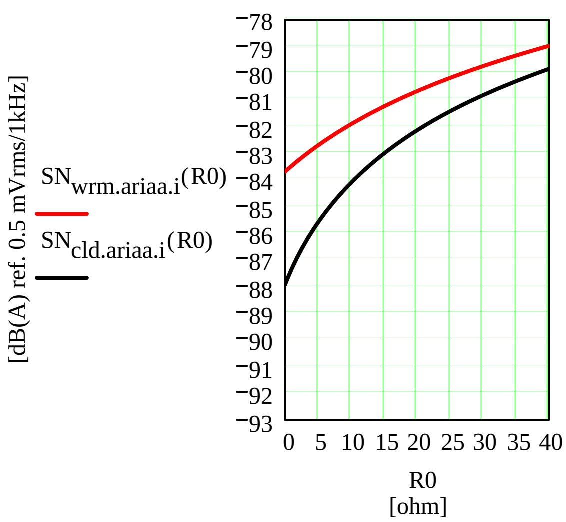

Fig. 10
Traces of the
R0-dependent input
referred warm &
cold SNs. (9) & (10)

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

$f := 20Hz, 25Hz .. 20kHz$

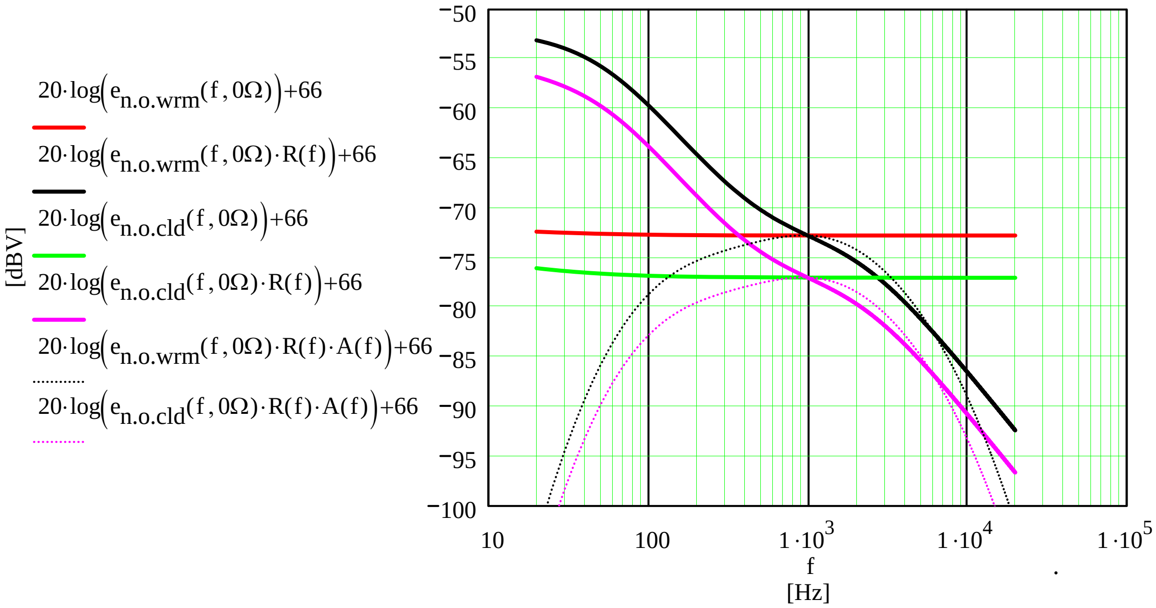

Fig. 12 Curves of the transformer noise after special treatments

Worsening = Delta red minus green at 1 kHz:

$$W_e(f, R0) := 20 \cdot \log\left(\frac{e_{n.o.wrm}(f, R0)}{e_{n.o.cld}(f, R0)}\right) \qquad W_e(h, 0\Omega) = 4.239 \quad [dB]$$