# Design of noise performance of feedback amplifiers

## The noisy nullor

With a high-gain controller the source-load transfer is predominantly determined by the feedback network

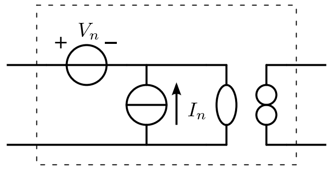
We will show that this is not the case for the noise behavior

- Equivalent input noise sources of the controller should be kept small
- Deterioration of the signal to noise ratio by the feedback network should be kept small

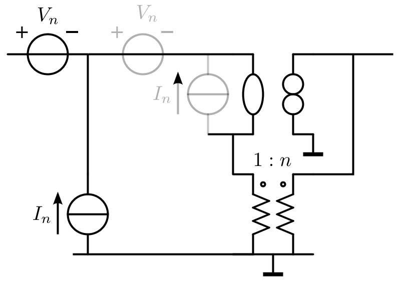
Study the noise behavior of nonenergic and passive feedback amplifiers

- Find rules for low-noise design
- Model the controller as a noisy nullor

  This enables orthogonal design of the noise behavior and of the static and dynamic transfer



### Noise performance of nonenergic feedback amplifiers



Redirect the current noise source via ground

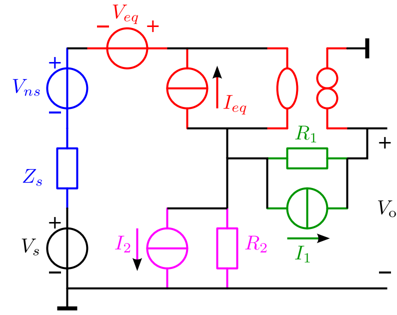
Replace the equivalent input current noise source of the transformer with an equivalent output current noise source; use:

$$AD=1, B=C=0$$

The current source in parallel with the output of the nullor can be ignored. Replacing it with equivalent input sources yields zero because:

$$A=B=C=D=0$$

### Noise performance of passive feedback amplifiers



Account for correlation:

Use unique name for power spectral densities of uncorrelated sources.

Add voltage or contributions of each uncorrelated source in one (complex) term.

Multiply the power spectral density with the squared magnitude of this term

$$S_{V_{\rm out}} = 4kT\mathrm{Re}(Z_s)\left(\frac{R_1+R_2}{R_2}\right)^2+S_{V_{eq}}\left(\frac{R_1+R_2}{R_2}\right)^2+S_{I_{eq}}\left(\frac{R_1+R_2}{R_2}\right)^2\left(Z_s+\frac{R_1R_2}{R_1+R_2}\right)^2+4kT\frac{R_1^2}{R_2}\ +4kTR_1$$

$$S_{V_s} = 4kT\mathrm{Re}(Z_s)+S_{V_{eq}}+S_{I_{eq}}\left(Z_s+\frac{R_1R_2}{R_1+R_2}\right)^2\boxed{+4kT\frac{R_1^2R_2}{(R_1+R_2)^2}+4kT\frac{R_1R_2^2}{(R_1+R_2)^2}}\longrightarrow +4kT\frac{R_1R_2}{R_1+R_2}$$

Conclusion:

The influence of the feedback resistors in the passive feedback voltage amplifier can be accounted for as if their parallel connection is in series with the source.

## SLiCAP noise analysis

```
#!/usr/bin/env python3
# -*- coding: utf-8 -*-

from SLiCAP import *

prj = initProject('Noisy Voltage Amplifier')

files = ['noisyVamp', 'noisyVampSimple']

noiseFigures = []

for fileName in files:

    makeNetlist(fileName + '.asc', fileName)
    i1 = instruction()
    i1.setCircuit(fileName + '.cir')
    i1.setSimType('symbolic')
    i1.setGainType('vi')
    i1.setDataType('noise')
    i1.setDetector('V_out')
    i1.setSource('V1')
    noiseResult = i1.execute()

    htmlPage('Noise Analysis')
    head2html('Circuit diagram')
    img2html(fileName + '.svg', 600, label = 'fig_' +
             fileName, caption = 'Schematics of ' + fileName + '.')
    noise2html(noiseResult)

    # Print the noise figure
    F  = noiseResult.inoise/noiseResult.inoiseTerms['V1']
    NF = 10*sp.log(F)/sp.log(10)
    noiseFigures.append(F)

ini.htmlIndex = 'index.html'
htmlPage('Noise figures')
head2html(files[0])
eqn2html('F', noiseFigures[0])
head2html(files[1])
eqn2html('F', noiseFigures[1])
head2html('Comparison')
Fdifference = sp.simplify(noiseFigures[0] - noiseFigures[1])
if sp.simplify(Fdifference) == 0:
    text2html('Both models have the same noise figure:')
else:
    text2html('Difference found between the noise figures obtained ' +
              'with the two models:')

eqn2html('F_' + files[0] + ' - F_' + files[1], Fdifference)
```

### Circuit diagram

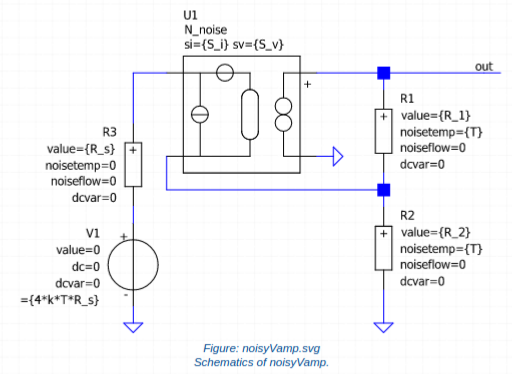


*Figure: noisyVamp.svg*
*Schematics of noisyVamp.*

### Symbolic noise analysis results

#### Detector-referred noise spectrum

$$S_{out} = \frac{4R_1^2Tk}{R_2}+4R_1Tk+\frac{4R_sTk(R_1+R_2)^2}{R_2^2}+\frac{S_i(R_1R_2+R_1R_s+R_2R_s)^2}{R_2^2}+\frac{S_v(R_1+R_2)^2}{R_2^2}\left[\frac{\mathrm{V}^2}{\mathrm{Hz}}\right]$$

#### Source-referred noise spectrum

$$S_{in} = \frac{4R_1^2R_2Tk}{(R_1+R_2)^2}+\frac{4R_1R_2^2Tk}{(R_1+R_2)^2}+4R_sTk+\frac{S_i(R_1R_2+R_1R_s+R_2R_s)^2}{(R_1+R_2)^2}+S_v\left[\frac{\mathrm{V}^2}{\mathrm{Hz}}\right]$$

#### Contributions of individual noise sources

Noise source: I1_XU1

| | | |
|---|---|---|
| Spectral density: | $S_i$ | $\left[\frac{\mathrm{A}^2}{\mathrm{Hz}}\right]$ |
| Detector-referred: | $\frac{S_i(R_1R_2+R_1R_s+R_2R_s)^2}{R_2^2}$ | $\left[\frac{\mathrm{V}^2}{\mathrm{Hz}}\right]$ |
| Source-referred: | $\frac{S_i(R_1R_2+R_1R_s+R_2R_s)^2}{(R_1+R_2)^2}$ | $\left[\frac{\mathrm{V}^2}{\mathrm{Hz}}\right]$ |

Noise source: I_noise_R1

| | | |
|---|---|---|
| Spectral density: | $\frac{4Tk}{R_1}$ | $\left[\frac{\mathrm{A}^2}{\mathrm{Hz}}\right]$ |
| Detector-referred: | $4R_1Tk$ | $\left[\frac{\mathrm{V}^2}{\mathrm{Hz}}\right]$ |
| Source-referred: | $\frac{4R_1R_2^2Tk}{(R_1+R_2)^2}$ | $\left[\frac{\mathrm{V}^2}{\mathrm{Hz}}\right]$ |

Noise source: I_noise_R2

| | | |
|---|---|---|
| Spectral density: | $\frac{4Tk}{R_2}$ | $\left[\frac{\mathrm{A}^2}{\mathrm{Hz}}\right]$ |
| Detector-referred: | $\frac{4R_1^2Tk}{R_2}$ | $\left[\frac{\mathrm{V}^2}{\mathrm{Hz}}\right]$ |
| Source-referred: | $\frac{4R_1^2R_2Tk}{(R_1+R_2)^2}$ | $\left[\frac{\mathrm{V}^2}{\mathrm{Hz}}\right]$ |

Noise source: V1

| | | |
|---|---|---|
| Spectral density: | $4R_sTk$ | $\left[\frac{\mathrm{V}^2}{\mathrm{Hz}}\right]$ |
| Detector-referred: | $\frac{4R_sTk(R_1+R_2)^2}{R_2^2}$ | $\left[\frac{\mathrm{V}^2}{\mathrm{Hz}}\right]$ |
| Source-referred: | $4R_sTk$ | $\left[\frac{\mathrm{V}^2}{\mathrm{Hz}}\right]$ |

Noise source: V1_XU1

| | | |
|---|---|---|
| Spectral density: | $S_v$ | $\left[\frac{\mathrm{V}^2}{\mathrm{Hz}}\right]$ |
| Detector-referred: | $\frac{S_v(R_1+R_2)^2}{R_2^2}$ | $\left[\frac{\mathrm{V}^2}{\mathrm{Hz}}\right]$ |
| Source-referred: | $S_v$ | $\left[\frac{\mathrm{V}^2}{\mathrm{Hz}}\right]$ |

### Circuit diagram

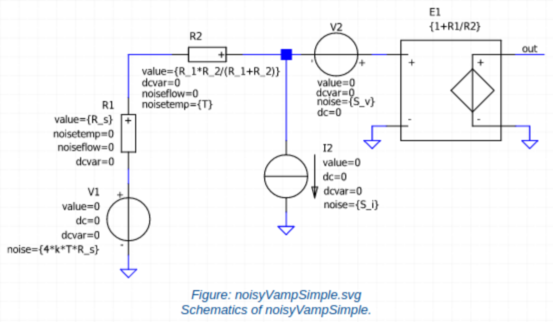


*Figure: noisyVampSimple.svg*
*Schematics of noisyVampSimple.*

### Symbolic noise analysis results

#### Detector-referred noise spectrum

$$S_{out} = \frac{4R_1R_2Tk(R_1+R_2)^2}{R_2^2(R_1+R_2)}+\frac{4R_sTk(R_1+R_2)^2}{R_2^2}+\frac{S_i(R_1+R_2)^2(R_1R_2+R_1R_s+R_2R_s)^2}{R_2^2(R_1+R_2)^2}+\frac{S_v(R_1+R_2)^2}{R_2^2}\left[\frac{\mathrm{V}^2}{\mathrm{Hz}}\right]$$

#### Source-referred noise spectrum

$$S_{in} = \frac{4R_1R_2Tk}{R_1+R_2}+4R_sTk+\frac{S_i(R_1R_2+R_1R_s+R_2R_s)^2}{(R_1+R_2)^2}+S_v\left[\frac{\mathrm{V}^2}{\mathrm{Hz}}\right]$$

#### Contributions of individual noise sources

Noise source: I2

| | | |
|---|---|---|
| Spectral density: | $S_i$ | $\left[\frac{\mathrm{A}^2}{\mathrm{Hz}}\right]$ |
| Detector-referred: | $\frac{S_i(R_1+R_2)^2(R_1R_2+R_1R_s+R_2R_s)^2}{R_2^2(R_1+R_2)^2}$ | $\left[\frac{\mathrm{V}^2}{\mathrm{Hz}}\right]$ |
| Source-referred: | $\frac{S_i(R_1R_2+R_1R_s+R_2R_s)^2}{(R_1+R_2)^2}$ | $\left[\frac{\mathrm{V}^2}{\mathrm{Hz}}\right]$ |

Noise source: I_noise_R2

| | | |
|---|---|---|
| Spectral density: | $\frac{4Tk(R_1+R_2)}{R_1R_2}$ | $\left[\frac{\mathrm{A}^2}{\mathrm{Hz}}\right]$ |
| Detector-referred: | $\frac{4R_1R_2Tk(R_1+R_2)^2}{R_2^2(R_1+R_2)}$ | $\left[\frac{\mathrm{V}^2}{\mathrm{Hz}}\right]$ |
| Source-referred: | $\frac{4R_1R_2Tk}{R_1+R_2}$ | $\left[\frac{\mathrm{V}^2}{\mathrm{Hz}}\right]$ |

Noise source: V1

| | | |
|---|---|---|
| Spectral density: | $4R_sTk$ | $\left[\frac{\mathrm{V}^2}{\mathrm{Hz}}\right]$ |
| Detector-referred: | $\frac{4R_sTk(R_1+R_2)^2}{R_2^2}$ | $\left[\frac{\mathrm{V}^2}{\mathrm{Hz}}\right]$ |
| Source-referred: | $4R_sTk$ | $\left[\frac{\mathrm{V}^2}{\mathrm{Hz}}\right]$ |

Noise source: V2

| | | |
|---|---|---|
| Spectral density: | $S_v$ | $\left[\frac{\mathrm{V}^2}{\mathrm{Hz}}\right]$ |
| Detector-referred: | $\frac{S_v(R_1+R_2)^2}{R_2^2}$ | $\left[\frac{\mathrm{V}^2}{\mathrm{Hz}}\right]$ |
| Source-referred: | $S_v$ | $\left[\frac{\mathrm{V}^2}{\mathrm{Hz}}\right]$ |

### Noisy Voltage Amplifier

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### Noise figures

#### noisyVamp

$$F=\frac{\frac{4R_1^2R_2Tk}{(R_1+R_2)^2}+\frac{4R_1R_2^2Tk}{(R_1+R_2)^2}+4R_sTk+\frac{S_i(R_1R_2+R_1R_s+R_2R_s)^2}{(R_1+R_2)^2}+S_v}{4R_sTk} \tag{1}$$

#### noisyVampSimple

$$F=\frac{\frac{4R_1^2R_2^2Tk\left(\frac{1}{R_2}+\frac{1}{R_1}\right)}{(R_1+R_2)^2}+4R_sTk+\frac{S_i(R_1R_2+R_1R_s+R_2R_s)^2}{(R_1+R_2)^2}+S_v}{4R_sTk} \tag{2}$$

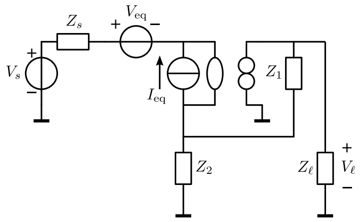
#### Comparison

Both models have the same noise figure:

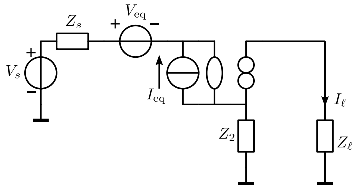
$$F_{noisyVamp}-F_{noisyVampSimple}=0 \tag{3}$$

## Single-loop passive feedback configurations and their equivalent input noise models

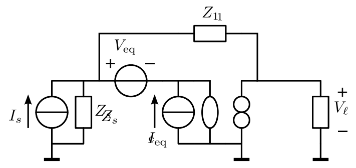
Voltage amplifier



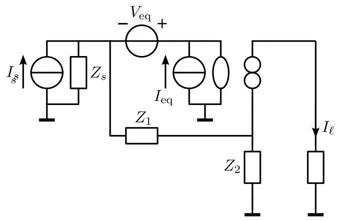
Transadmittance



Transimpedance

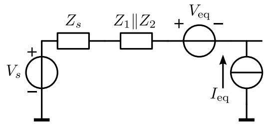


Current amplifier

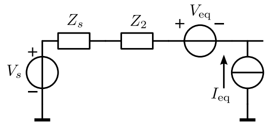


The noise contribution of the feedback impedances and their influence on the contribution of the equivalent input noise sources of the controller can be found:

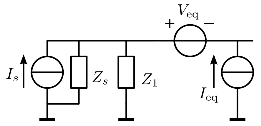
As if the parallel connection of the feedback impedances is in series with the source



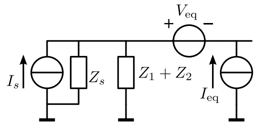
As if the feedback impedance is in series with the source

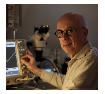


As if the feedback impedance is in parallel with the source



As if the series connection of the feedback impedances is in series with the source





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