Low Distortion Oscillator Performance Measurements

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Contents

Chapter 1

Introduction

In this document I present the performance measurements I have carried out on my latest low distortion RC oscillator design. To verify the performance I focussed mainly on total harmonic distortion and noise (THD+N) measurements. In addition to this amplitude flatness was analyzed. To compare the performance with existing low distortion oscillators, I have carried out the same measurements on the low distortion sine wave generator of the Audio Precision SYS-2722 audio analyzer.

Together with a matching distortion analyzer, my oscillator is intended for high resolution distortion measurements on audio and other low-frequency circuits. A photograph of my low distortion oscillator is shown in figure 1.1. The final PCB iteration for it was finished in June 2017. While the matching distortion analyzer is yet to be designed, I hope to achieve a THD+N system residual (that is the THD+N measured when the oscillator is connected directly to the distortion analyzer) of less than −120 dB in a 20 Hz–22 kHz measurement bandwidth. The THD system residual should be well below the THD+N system residual. Otherwise distortion cancellation between the measurement system and the device under test could significantly affect a THD+N measurement. To provide sufficient margin for the noise and distortion contribution of the matching distortion analyzer, I tried to reduce the THD+N of the oscillator to less than −125 dB and its THD to less than −140 dB. The mentioned THD and THD+N figures for the system residual and oscillator performance apply to frequencies up to about 20 kHz and amplitudes above about 0 dBu only. At higher frequencies or at lower amplitudes such performance figures would be difficult to achieve. With respect to amplitude flatness I have designed the oscillator to achieve less than ±0.1 dB from 10 Hz to 10 kHz and ±0.5 dB from 10 Hz to 100 kHz.

To measure the oscillator performance I have used the Audio Precision SYS-2722 audio analyzer. Its lowest THD+N floor is around −122 dB in a 20 Hz–22 kHz measurement bandwidth. The floor, however, degrades to above −115 dB for many frequency and amplitude combinations. Thus the SYS-

Figure 1.1: My low distortion oscillator with external power supply

2722 audio analyzer cannot directly verify the intended oscillator THD+N performance of −125 dB. To achieve higher resolution I have subtracted the noise contribution of the analyzer. This is a powerful technique that can reduce the THD+N floor of the SYS-2722 audio analyzer to around −130 dB, but the resulting measurement uncertainty is not easy to quantify. Particularly at amplitudes below −10 dBu, the analyzer noise subtraction is sensitive to random fluctuations of the THD+N reading due to noise and can introduce significant measurement errors.

In contrast, the amplitude flatness measurements are much easier to carry out. The SYS-2722 audio analyzer is specified for an amplitude flatness of ±0.008 dB from 20 Hz to 20 kHz and of ±0.1 dB from 10 Hz to 120 kHz. As the typical performance of the specimen used for these measurements appears to be much better than the guaranteed specifications, the amplitude flatness of my oscillator (less than ±0.1 dB from 10 Hz to 10 kHz and ±0.5 dB from 10 Hz to 100 kHz) can be verified by direct measurement.

The frequency range of my oscillator reaches from 10 Hz to 100 kHz and in each decadic range 6 logarithmically spaced frequencies can be selected. The differential output amplitude range covers −89.9 dBu to +30.0 dBu. 0.1 dB amplitude resolution is achieved by switching the output amplifier gain while an output attenuator provides coarse amplitude ranging in 10 dB steps. Single-ended output levels are 6 dB lower than the stated differential range. Covering all possible combinations of frequency and amplitude in the measurements is not feasible. Instead I have run THD+N measurements versus amplitude for a representative selection of frequencies and versus frequency for a representative selection of amplitudes. The amplitude flatness measurements were also carried out for a representative selection of amplitudes.

For frequencies from 33 Hz to 1 kHz and for amplitudes above −10 dBu, the measurements presented later in this document show that my oscillator achieves a THD+N in the range of −130 dB to −125 dB. At frequencies below 33 Hz, the actual oscillator THD+N is probably in a similar range but the distortion contribution from the SYS-2722 audio analyzer dominates the readings. At frequencies above 1 kHz, the THD+N of my oscillator falls in the range of −125 dB to −122 dB. The higher THD+N is caused by oscillator noise. At amplitudes below −10 dBu, the oscillator THD+N is probably similar to the THD+N at higher amplitudes. But as mentioned before, the subtraction of the analyzer noise becomes less reliable and significant measurement errors must be expected.

The measured amplitude flatness of my oscillator is ±0.02 dB from 10 Hz to 100 kHz. This is much better than the intended performance of less than ±0.1 dB from 10 Hz to 10 kHz and ±0.5 dB from 10 Hz to 100 kHz.

The detailed results are presented in the following chapters as follows. Chapter 2.1 and 2.2 show the THD+N measurements. In chapter 2.3, amplitude flatness results are presented. In the appendix A, the oscillator and analyzer settings used for the measurements are listed. Appendix B discusses the analyzer noise subtraction procedure that is used to achieve higher THD+N measurement resolution.

Chapter 2

Measurement Results

2.1 THD+N Versus Amplitude

The following figures show the THD+N performance versus amplitude for my low distortion oscillator and the low distortion sine wave generator of the Audio Precision SYS-2722 audio analyzer. Both oscillators are measured at decadic frequencies between 10 Hz and 100 kHz, with amplitudes ranging from −20 dBu to +30 dBu. The maximum output amplitude of the SYS-2722 is reduced at 10 Hz and 100 kHz; therefore these sweeps run only up to +24 dBu.

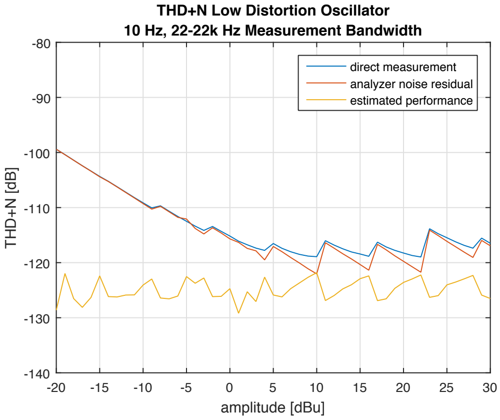
To measure THD+N, the SYS-2722 analyzer is used. The analyzer measurement bandwidth is set to 22 Hz–22 kHz for frequencies from 10 Hz to 1 kHz, to 22 Hz–80 kHz for the 10 kHz frequency and to 22 Hz–500 kHz for the 100 kHz frequency.

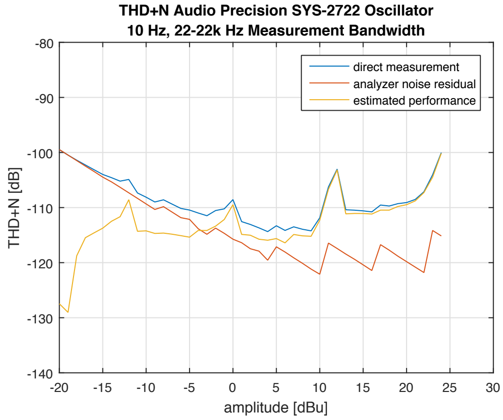
Each graph shows three traces: the direct THD+N measurement of the oscillator, the analyzer noise contribution to the direct measurement, and the THD+N where the analyzer noise contribution is subtracted from the direct measurement (labeled *estimated performance*). The third trace is closest to the actual performance of the oscillator at medium and high amplitudes. At amplitudes below −10 dBu though, the analyzer noise subtraction becomes unreliable. Also note that the analyzer distortion contribution is not reduced in the third trace. For further details on the analyzer noise subtraction see appendix B.

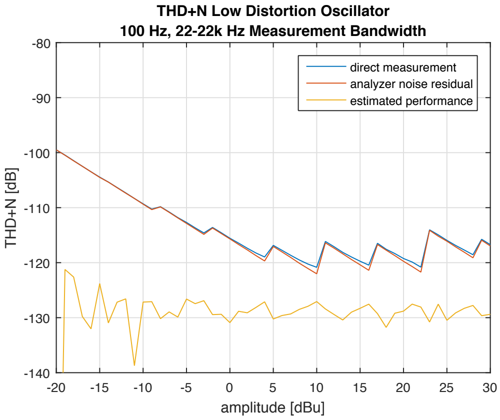
Because of the gain ranging of the analyzer, the measurements show a sawtooth-like periodicity of 6 dB. Within a given range, the noise contribution of the analyzer drops towards higher input amplitudes while its distortion contribution rises. In the direct measurement the noise contribution of the analyzer is dominant and thus the THD+N reading is lowest at the upper end of each range. After noise subtraction, however, only the analyzer distortion contribution remains. Thus for this trace the reading is lowest at the lower end of each range.

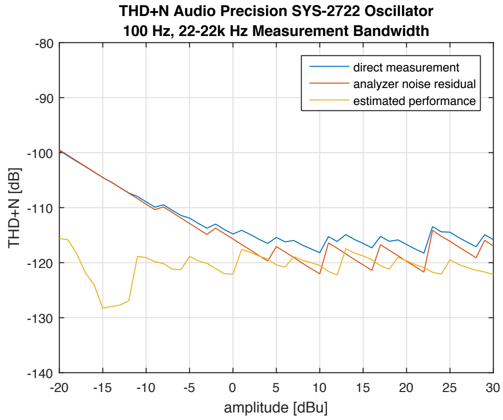
At 100 kHz, distortion from the output amplifier contributes significantly to the THD+N of my low distortion oscillator. The gain ranging of the output amplifier results in a sawtooth-like periodicity of 10 dB where towards the upper end of each range the distortion rises rapidly. At the lower end of each range, the THD+N is dominated by noise.

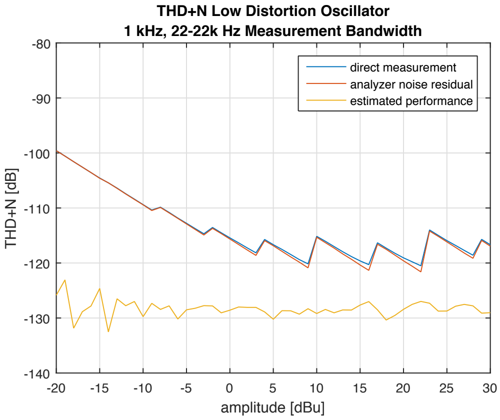
Equipped with an output transformer, the SYS-2722 oscillator shows significant distortion at 10 Hz. At higher frequencies, the gain ranging of the output amplifier (6 dB steps) is visible.

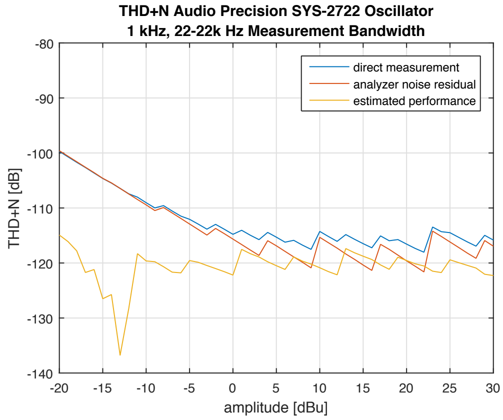

THD+N Low Distortion Oscillator
10 Hz, 22-22k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
amplitude [dBu]

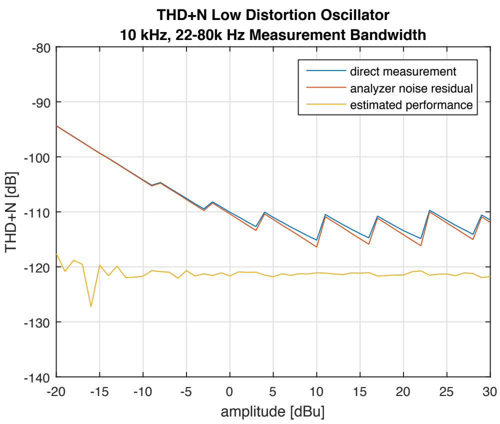

THD+N Audio Precision SYS-2722 Oscillator
10 Hz, 22-22k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
amplitude [dBu]

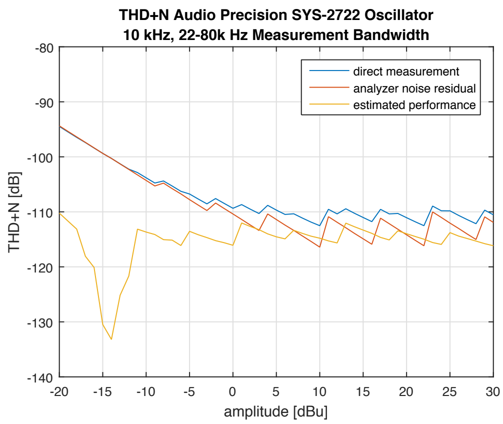

THD+N Low Distortion Oscillator
100 Hz, 22-22k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
amplitude [dBu]

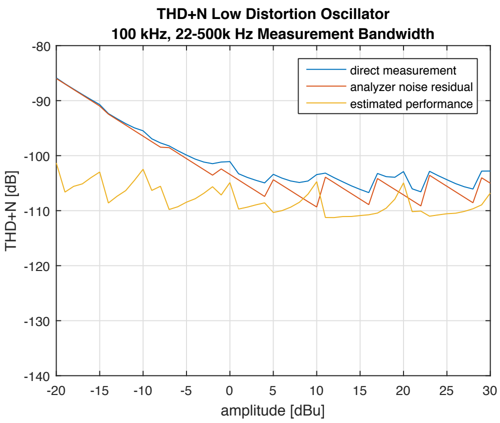

THD+N Audio Precision SYS-2722 Oscillator
100 Hz, 22-22k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
amplitude [dBu]

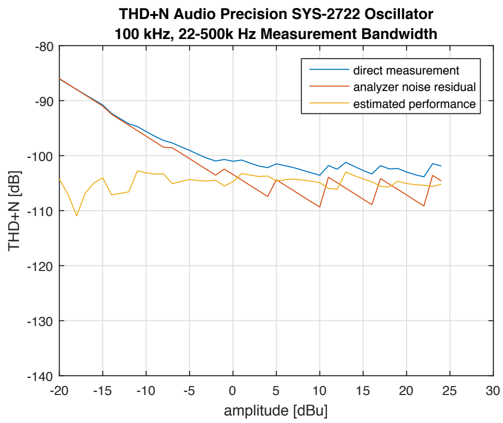

THD+N Low Distortion Oscillator
1 kHz, 22-22k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
amplitude [dBu]


THD+N Audio Precision SYS-2722 Oscillator
1 kHz, 22-22k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
amplitude [dBu]


THD+N Low Distortion Oscillator
10 kHz, 22-80k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
-80
-90
-100
-110
-120
-130
-140
-20
-15
-10
-5
0
5
10
15
20
25
30
amplitude [dBu]


THD+N Audio Precision SYS-2722 Oscillator
10 kHz, 22-80k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
-80
-90
-100
-110
-120
-130
-140
-20
-15
-10
-5
0
5
10
15
20
25
30
amplitude [dBu]


THD+N Low Distortion Oscillator
100 kHz, 22-500k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
-80
-90
-100
-110
-120
-130
-140
-20
-15
-10
-5
0
5
10
15
20
25
30
amplitude [dBu]


THD+N Audio Precision SYS-2722 Oscillator
100 kHz, 22-500k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
-80
-90
-100
-110
-120
-130
-140
-20
-15
-10
-5
0
5
10
15
20
25
30
amplitude [dBu]

2.2 THD+N Versus Frequency

The following figures show the THD+N performance versus frequency for my low distortion oscillator and the low distortion sine wave generator of the Audio Precision SYS-2722. Both oscillators are measured with the SYS-2722 audio analyzer at amplitudes from 0 dBu to +30 dBu in 10 dBu steps. At each of these amplitudes, the oscillators are measured in three different frequency ranges with different analyzer measurement bandwidths:

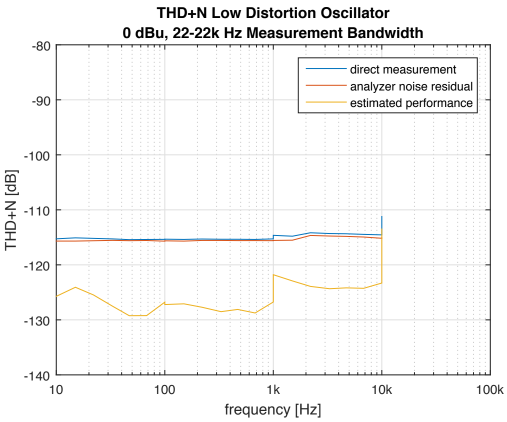
- 10 Hz to 10 kHz with a measurement bandwidth of 22 Hz–22 kHz;
- 10 Hz to 47 kHz with a measurement bandwidth of 22 Hz–80 kHz;
- 10 Hz to 100 kHz with a measurement bandwidth of 22 Hz–500 kHz.

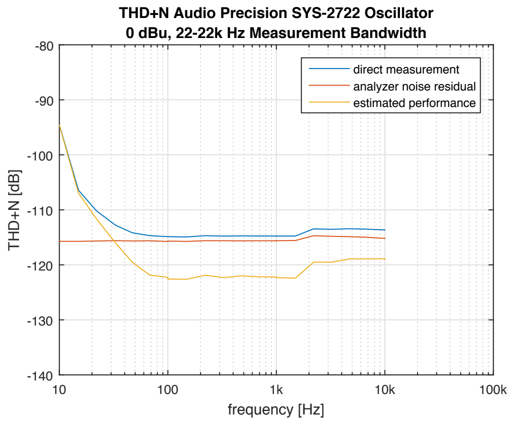
The maximum output amplitude of the SYS-2722 is reduced at 10 Hz and 100 kHz; therefore the sweep at +30 dBu amplitude runs only from 22 Hz to 47 kHz.

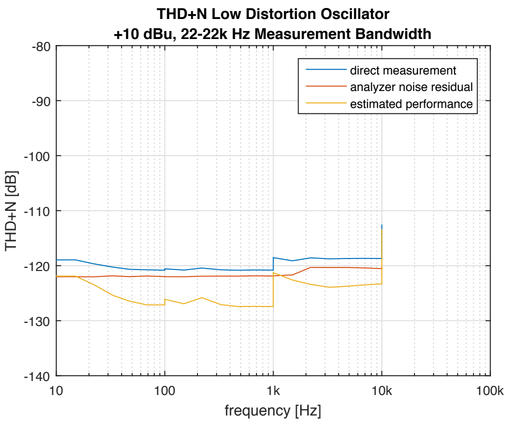
Each graph shows three traces: the direct THD+N measurement of the oscillator, the analyzer noise contribution to the direct measurement, and the THD+N where the analyzer noise contribution is subtracted from the direct measurement (labeled *estimated performance*). The third trace is closest to the actual performance of the oscillator. Note, however, that the analyzer distortion contribution is not reduced in the third trace. For further details on the analyzer noise subtraction see appendix B.

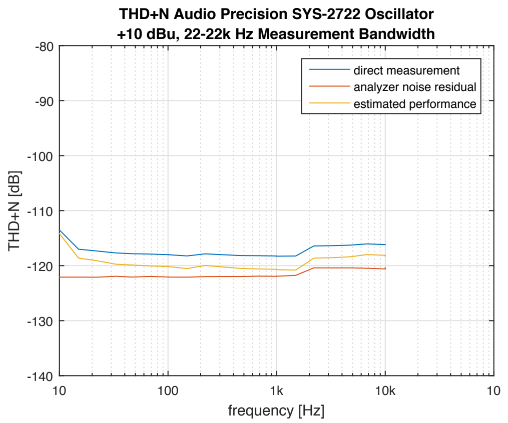
In my low distortion oscillator, the decadic frequency ranging points lie at 100 Hz, 1 kHz, and 10 kHz. At these frequencies, impedance level changes in the oscillator circuit result in abrupt changes of oscillator noise. This is reflected in the measurements as equally abrupt changes in THD+N.

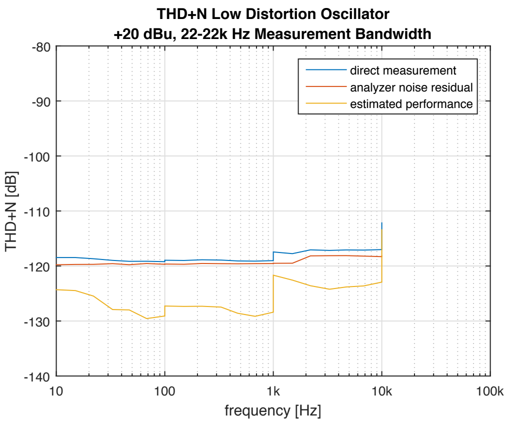
In the SYS-2722 oscillator, the decadic frequency ranging points and the resulting changes in THD+N lie at 200 Hz, 2 kHz and 20 kHz. The effect is less clearly visible than in my oscillator; this is presumably because the noise of the output amplifier (which is independent from frequency) masks the noise from the oscillator. Below 100 Hz, the output transformer of the SYS-2722 oscillator causes significant distortion. The distortion is particularly high at 0 dBu and +30 dBu.

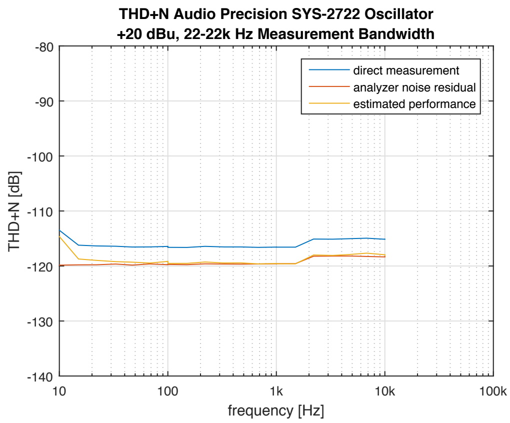

THD+N Low Distortion Oscillator
0 dBu, 22-22k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
-80
-90
-100
-110
-120
-130
-140
10
100
1k
10k
100k
frequency [Hz]


THD+N Audio Precision SYS-2722 Oscillator
0 dBu, 22-22k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
-80
-90
-100
-110
-120
-130
-140
10
100
1k
10k
100k
frequency [Hz]


THD+N Low Distortion Oscillator
+10 dBu, 22-22k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
-80
-90
-100
-110
-120
-130
-140
10
100
1k
10k
100k
frequency [Hz]


THD+N Audio Precision SYS-2722 Oscillator
+10 dBu, 22-22k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
-80
-90
-100
-110
-120
-130
-140
10
100
1k
10k
10
frequency [Hz]


THD+N Low Distortion Oscillator
+20 dBu, 22-22k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
-80
-90
-100
-110
-120
-130
-140
10
100
1k
10k
100k
frequency [Hz]


THD+N Audio Precision SYS-2722 Oscillator
+20 dBu, 22-22k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
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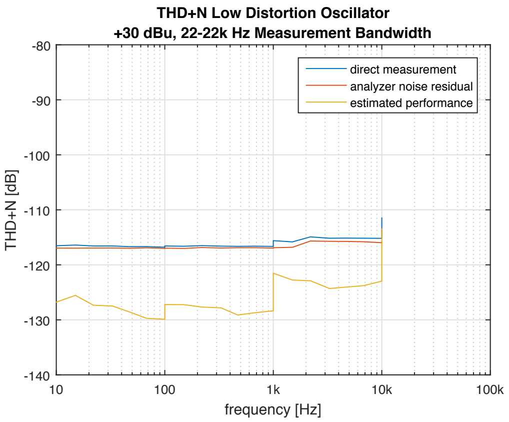
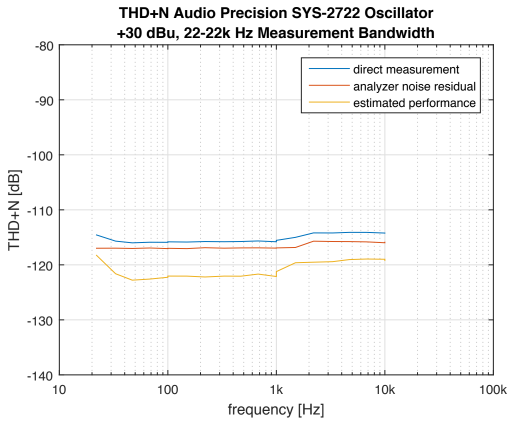
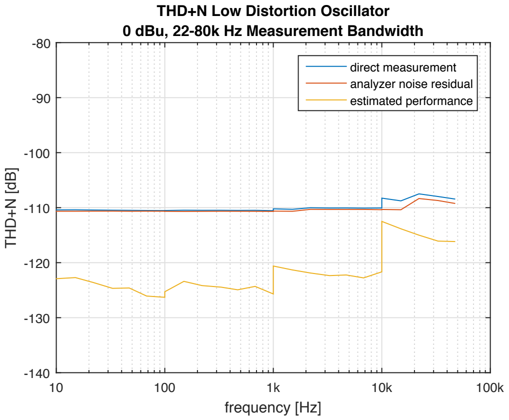
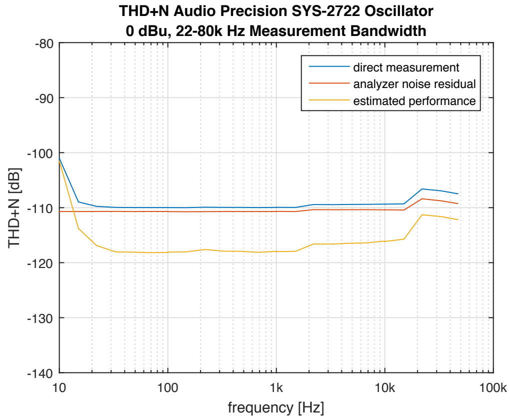
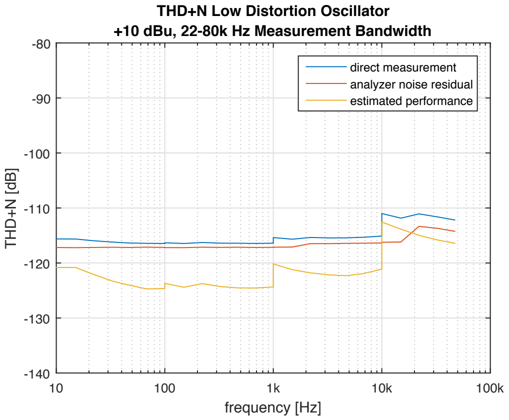
-90
-100
-110
-120
-130
-140
10
100
1k
10k
100k
frequency [Hz]

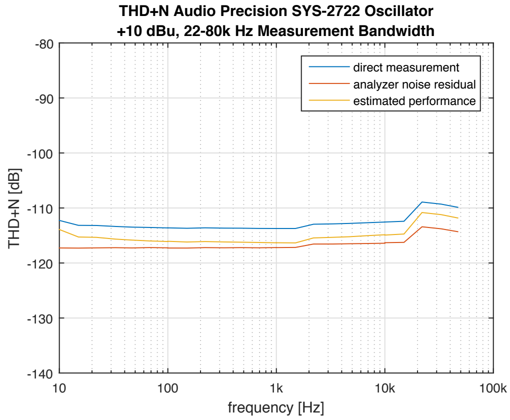

THD+N Low Distortion Oscillator
+30 dBu, 22-22k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
frequency [Hz]
-80
-90
-100
-110
-120
-130
-140
10
100
1k
10k
100k

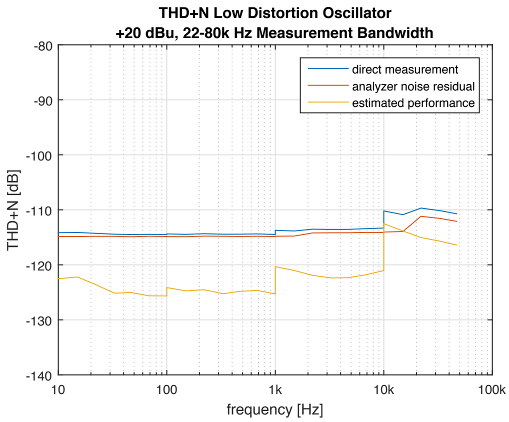

THD+N Audio Precision SYS-2722 Oscillator
+30 dBu, 22-22k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
frequency [Hz]
-80
-90
-100
-110
-120
-130
-140
10
100
1k
10k
100k

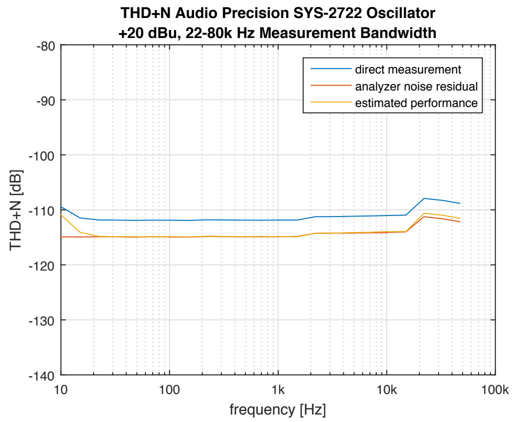

THD+N Low Distortion Oscillator
0 dBu, 22-80k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
frequency [Hz]
-80
-90
-100
-110
-120
-130
-140
10
100
1k
10k
100k

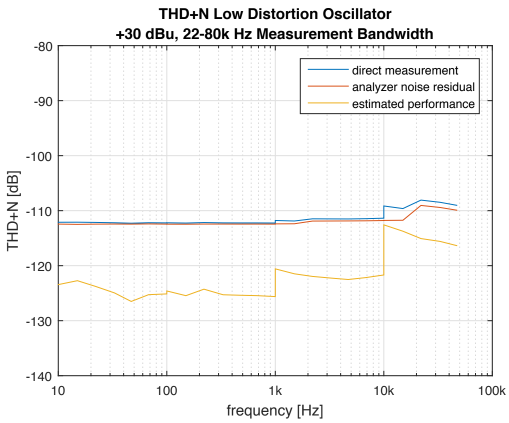

THD+N Audio Precision SYS-2722 Oscillator
0 dBu, 22-80k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
frequency [Hz]
-80
-90
-100
-110
-120
-130
-140
10
100
1k
10k
100k


THD+N Low Distortion Oscillator
+10 dBu, 22-80k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
frequency [Hz]
-80
-90
-100
-110
-120
-130
-140
10
100
1k
10k
100k


THD+N Audio Precision SYS-2722 Oscillator
+10 dBu, 22-80k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
frequency [Hz]
-80
-90
-100
-110
-120
-130
-140
10
100
1k
10k
100k


THD+N Low Distortion Oscillator
+20 dBu, 22-80k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
frequency [Hz]


THD+N Audio Precision SYS-2722 Oscillator
+20 dBu, 22-80k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
frequency [Hz]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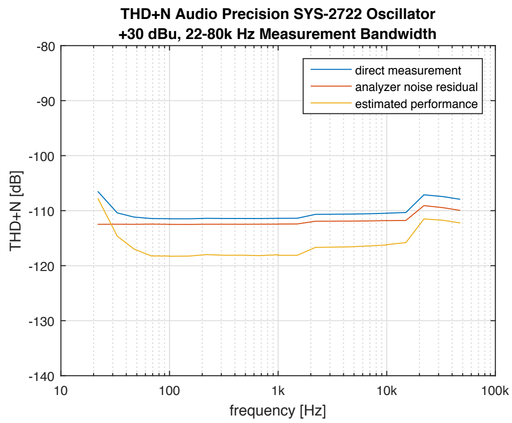
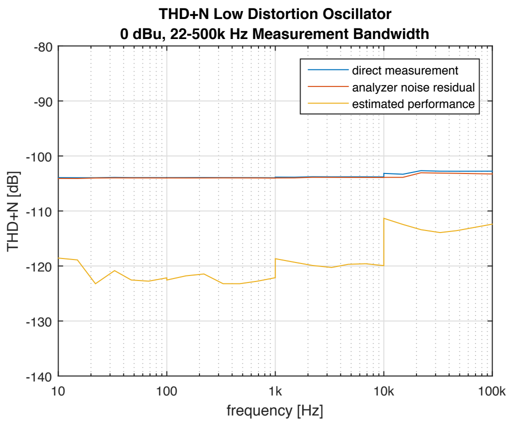
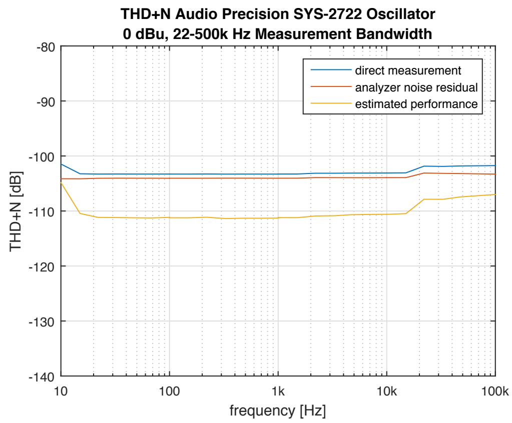
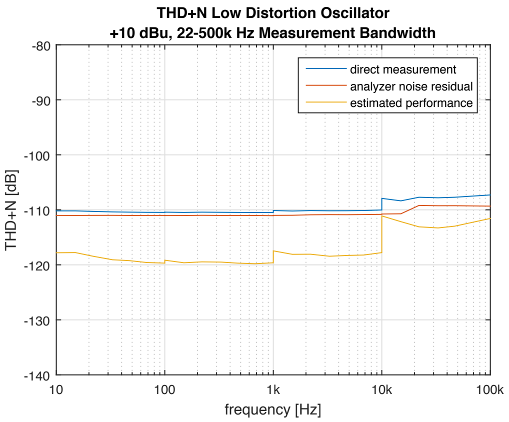
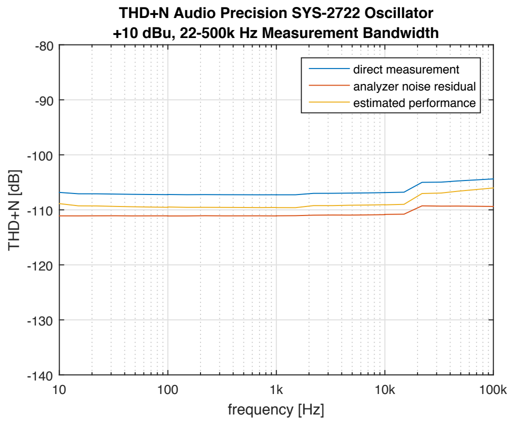
+30 dBu, 22-80k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
frequency [Hz]

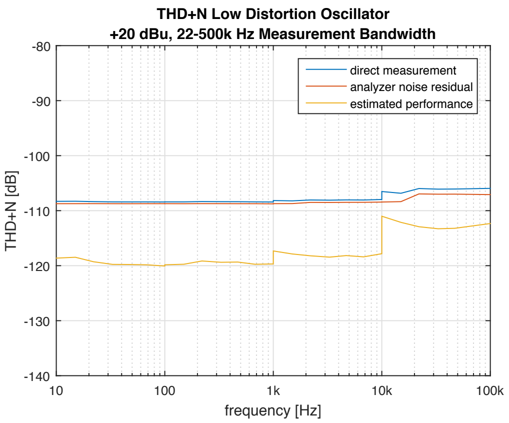

THD+N Audio Precision SYS-2722 Oscillator
+30 dBu, 22-80k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
frequency [Hz]

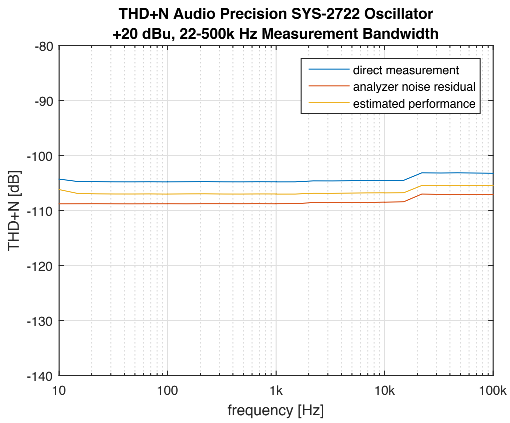

THD+N Low Distortion Oscillator
0 dBu, 22-500k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
frequency [Hz]

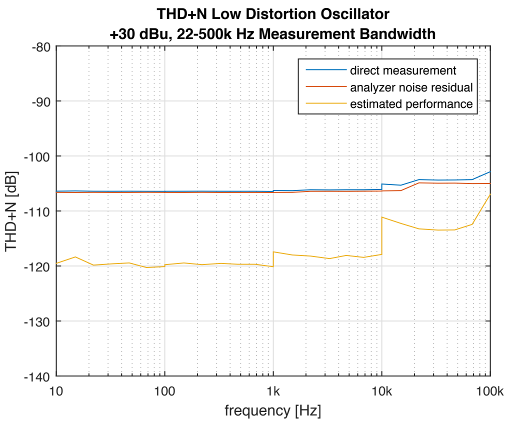

THD+N Audio Precision SYS-2722 Oscillator
0 dBu, 22-500k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
frequency [Hz]

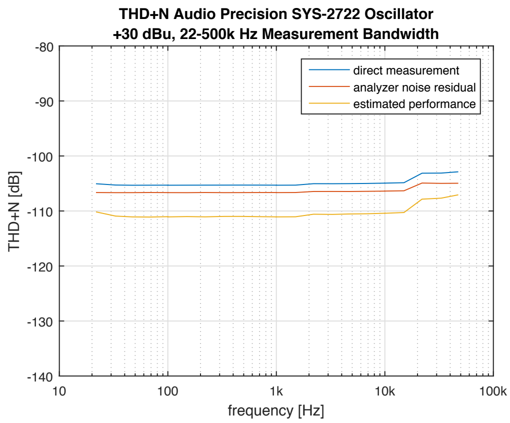

THD+N Low Distortion Oscillator
+10 dBu, 22-500k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
frequency [Hz]


THD+N Audio Precision SYS-2722 Oscillator
+10 dBu, 22-500k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
frequency [Hz]


THD+N Low Distortion Oscillator
+20 dBu, 22-500k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
frequency [Hz]


THD+N Audio Precision SYS-2722 Oscillator
+20 dBu, 22-500k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
frequency [Hz]

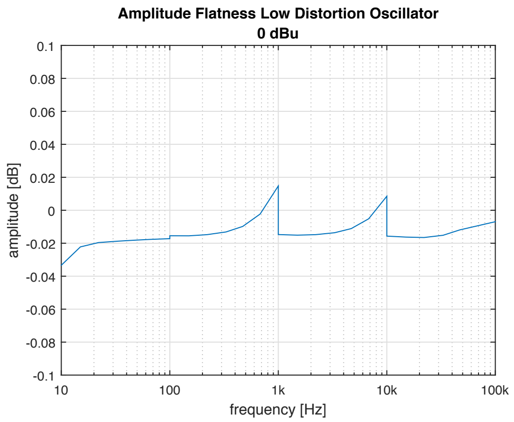

THD+N Low Distortion Oscillator
+30 dBu, 22-500k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
frequency [Hz]

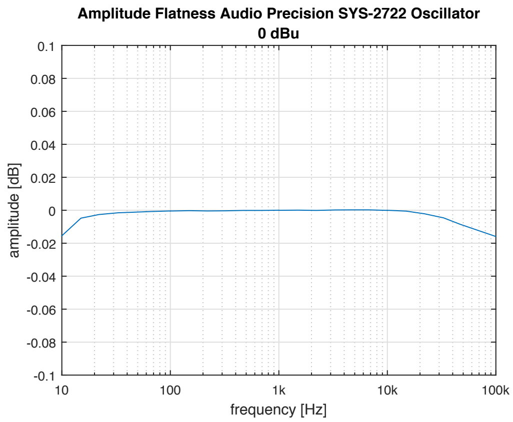

THD+N Audio Precision SYS-2722 Oscillator
+30 dBu, 22-500k Hz Measurement Bandwidth
direct measurement
analyzer noise residual
estimated performance
THD+N [dB]
frequency [Hz]

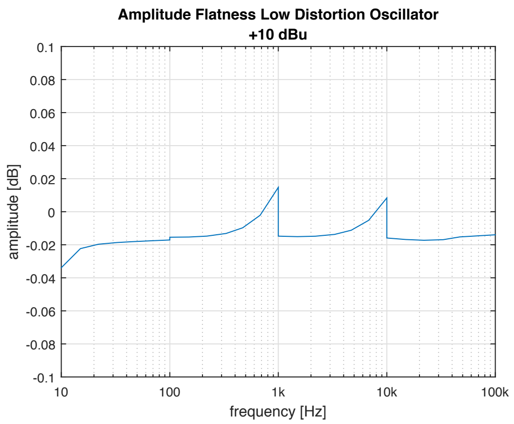
2.3 Amplitude Flatness

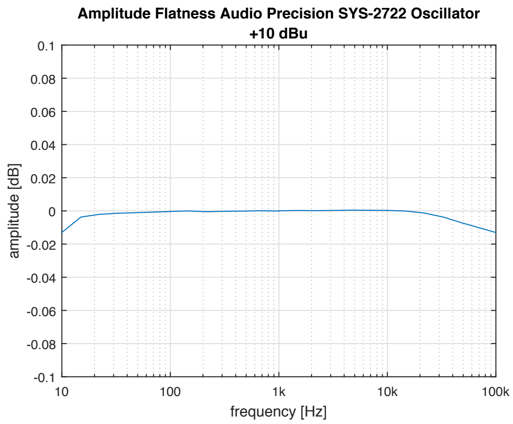
The following figures show the amplitude flatness of my low distortion oscillator and the low distortion sine wave generator of the Audio Precision SYS-2722. Both oscillators are measured at amplitudes from 0 dBu to +30 dBu in 10 dBu steps using the SYS-2722 audio analyzer. Each measurement is normalized at 1 kHz. Because the maximum output amplitude of the SYS-2722 low distortion sine wave generator is reduced at 10 Hz and 100 kHz, the sweep at +30 dBu amplitude runs only from 22 Hz to 47 kHz.

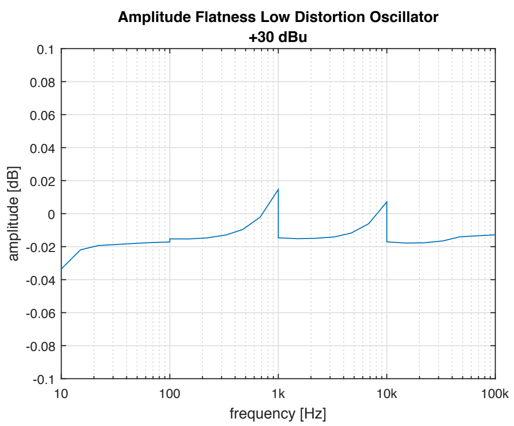
My low distortion oscillator is not particularly optimized for amplitude flatness. The amplitude jumps at 1 kHz and 10 kHz are the result of a low-pass filter in the amplitude control loop of the oscillator that is switched with the range setting of the oscillator frequency. This low-pass filter is present in the circuit to reduce amplitude modulation noise of the oscillator signal.

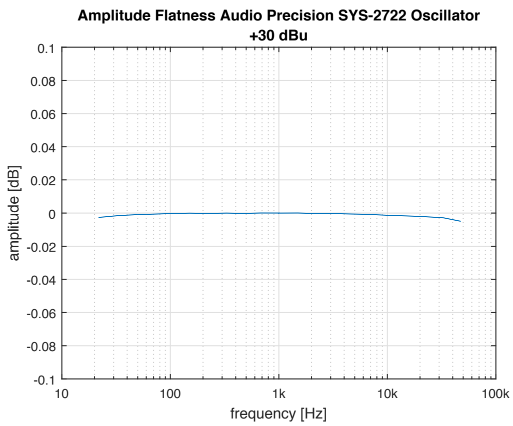

Amplitude Flatness Low Distortion Oscillator
0 dBu
amplitude [dB]
frequency [Hz]
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
10
100
1k
10k
100k


Amplitude Flatness Audio Precision SYS-2722 Oscillator
0 dBu
amplitude [dB]
frequency [Hz]
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
10
100
1k
10k
100k


Amplitude Flatness Low Distortion Oscillator
+10 dBu
amplitude [dB]
frequency [Hz]
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
10
100
1k
10k
100k


Amplitude Flatness Audio Precision SYS-2722 Oscillator
+10 dBu
amplitude [dB]
frequency [Hz]
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
10
100
1k
10k
100k


Amplitude Flatness Low Distortion Oscillator
+30 dBu
amplitude [dB]
frequency [Hz]
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
10
100
1k
10k
100k


Amplitude Flatness Audio Precision SYS-2722 Oscillator
+30 dBu
amplitude [dB]
frequency [Hz]
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
10
100
1k
10k
100k

Appendix A

Oscillator and Analyzer Settings

For all measurements shown in this document, my low distortion oscillator was used with the following settings:

- balanced output, grounded, 100 Ω differential output impedance
- injection-locking: *off*

I haven't taken a note for the settings of the SYS-2722 low distortion sine wave generator, but likely I've used the following settings:

- balanced output, grounded, 40 Ω differential output impedance
- frequency accuracy mode: *high accuracy mode*

The SYS-2722 audio analyzer settings were as follows:

- balanced input, 200 kΩ differential input impedance, DC-coupled
- RMS detector, 4 readings per second
- bandpass/bandreject frequency: *fixed* (i.e. manually set to the frequency of the oscillator)

Appendix B

Analyzer Noise Subtraction

The floor of THD+N measurements is limited by the noise of the distortion analyzer. To lower the floor, the distortion analyzer noise can be subtracted from a direct THD+N measurement. The following procedure is used for the measurements shown in this document:

- the oscillator under test is set to the desired level;
- the automatic gain ranging of the distortion analyzer is enabled;
- the automatic gain ranging of the distortion analyzer is disabled;
- a first THD+N measurement is taken;
- the oscillator level is reduced by 20 dB;
- a second THD+N measurement is taken and scaled by −20 dB to correct for the reduced oscillator level;
- the second THD+N measurement is root-mean-square subtracted from the first.

The second THD+N measurement is taken with a reduced oscillator level to ensure that the measurement is dominated by the noise of the distortion analyzer. The automatic gain ranging of the distortion analyzer is disabled beforehand to ensure that the second THD+N measurement is taken with the same gain range as the first THD+N measurement. This is necessary because the noise of the distortion analyzer is different for each gain range.

The root-mean-square subtraction in the last step has to be done in the linear domain. This means that THD+N measurements in Decibels are converted to linear figures before the root-mean-square subtraction, and then converted back to Decibels.

Analyzer noise subtraction is sensitive to random fluctuations of the THD+N readings due to noise. To reduce this effect, the THD+N measurements are averaged 40 times each. Nonetheless, at oscillator levels below

−10 dBu, the analyzer noise subtraction becomes unreliable. This is because at these low levels, the distortion analyzer noise is considerably higher than the noise of the oscillator. Thus the subtraction becomes particularly sensitive to the exact measurement of the analyzer noise contribution.

Note that the analyzer distortion contribution is not reduced by noise subtraction. The distortion of the SYS-2722 rises towards the upper end of each gain range, and is particularly pronounced at frequencies below 33 Hz.