An ultra low-distortion oscillator with THD below -140 dB

Vojtěch Janásek, www.janascard.cz (Actualized 9/2020)

Abstract: *ADC circuits that resolve signal into 20 or more bits need a low-noise signal source for measuring parameters such as harmonic distortion or effective number of bits. A notch filter removes the fundamental frequency from the oscillator's signal for testing harmonic distortion. (Actualization 9/2020 - switching from LME49710 to OPA1656)*

A low-distortion oscillator is necessary for testing today's ADCs (analog-to-digital converters) that have resolution higher than 20 bits. Low-distortion amplifiers with THD (total-harmonic distortion) of -120 dB or less also need such an oscillator for testing. Commercially available distortion meters offer many measurement functions, but even the best have a THD measurement limit somewhere
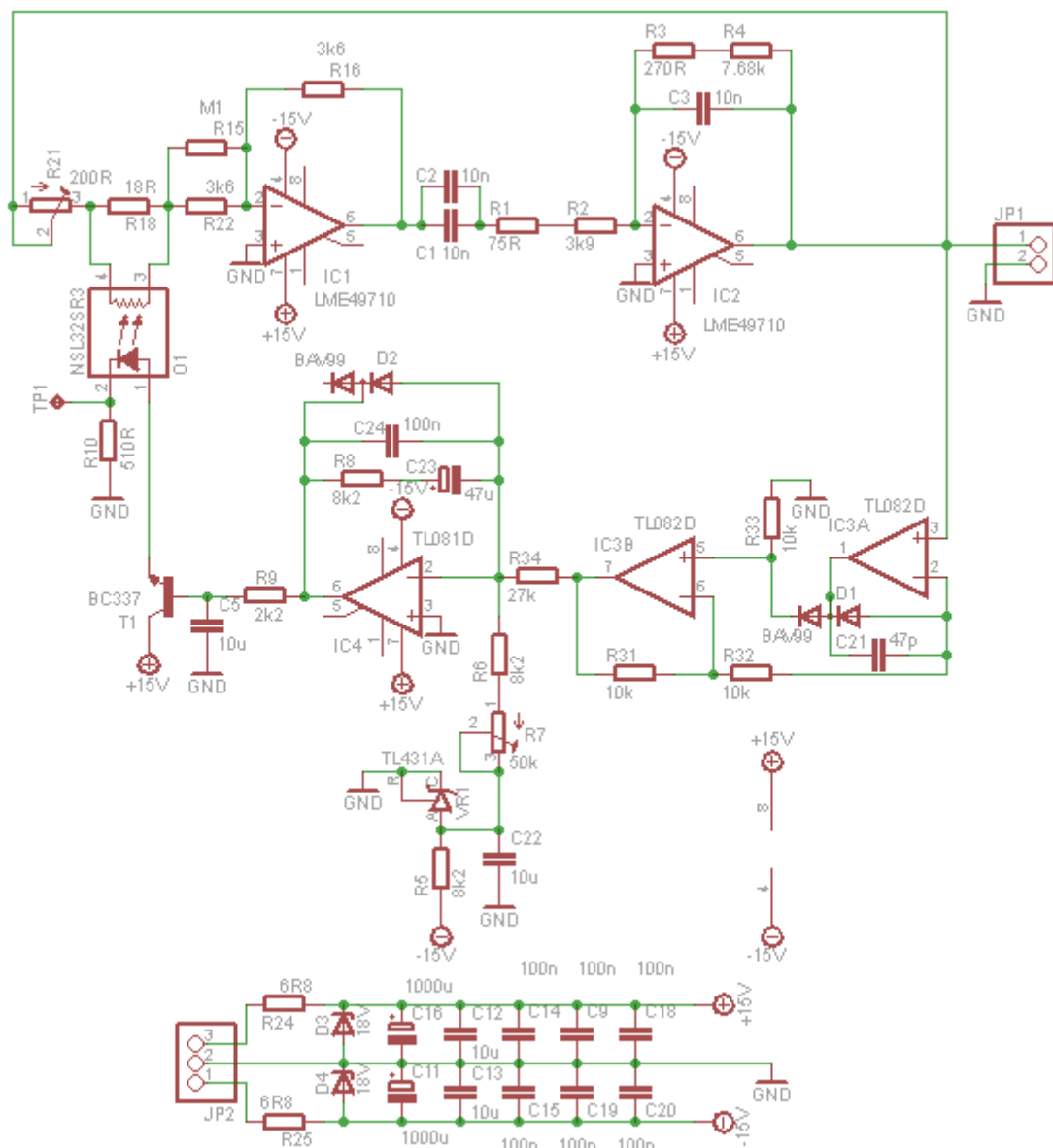

Fig. 1 Ultra-low distortion oscillator

around –115 dB (Ref 1).

Several low-distortion oscillator designs have been published, but they also have THD of –120 dB or slightly better (Refs. 2, 3, 4). At JanasCard, we've developed an oscillator with THD below –140 dB that we use for in-house testing.

The oscillator in **Figure 1** uses an inverted Wien-bridge topology with amplitude stabilization through a LED-driven CdS (cadmium-sulfide) photocell isolator. IC_1 and IC_2 are low noise, high linearity LME49710 audio amplifiers from Texas Instruments, key components of the oscillator. These amplifiers have nonlinearity below 0.1 ppm in inverting mode (Ref. 5). IC_1 acts as an inverter with gain –1. IC_2, in conjunction with R_1, R_2, R_3, R_4, C_1, C_2, and C_3, forms a band-pass filter that sets the oscillator's resonant frequency to 2 kHz. The design uses a Wien bridge with values R, C, R/2, and 2C because it the oscillator needs an inverting gain of –1.

You can use a simpler configuration with equal values for R and C, (Ref. 4) but it requires an inverter with a gain of –2 and you must take the output from the inverting amplifier stage. The resulting noise is significantly higher because of the higher overall gain and the circuit isn't bandwidth limiting.

Noise is also an important parameter for ADC testing. Thus, we used SPICE simulation on the oscillator's noise performance. **Figure 2** shows that the circuit's voltage noise-spectral density is highest at the resonant frequency and then falls at higher frequencies because of band-pass filtering. Total noise in the 20 Hz-30 kHz band is 1.7µV. That gives a theoretical SNR (signal-to-noise ratio) of 126 dB for output level 10 V_{PP}, or 3.5 V_{RMS}. The LM49710 has voltage-noise density of 2.5 nV/$\sqrt{Hz}$. Resistors and input noise currents of the amplifiers also add to the overall noise. If the lowest possible noise is important, you can use lower resistor values, but that's at the expense of higher power consumption and increased distortion. The LM49710 distortion performance is specified with minimum load resistance of 600 Ω.

For amplitude stabilization, the oscillator's AGC (automatic gain control) circuit consists of a full-wave rectifier with high input impedance (IC_{3A}, IC_{3B}), integrator IC_4, and optocoupler O_1. The voltage across the optocoupler's photo-resistor is only 18 mV as set by the 18-Ω parallel resistor R_{18}. That voltage keeps the voltage across O_1 to a negligible level. Multiturn trim potentiometer R_{21} sets the AGC's working point to roughly 10 mA through O1's LED (5 V at TP_1). Turn R_{21} slowly until the AGC locks, loop's time constant is several seconds. The setting is quite sensitive because of the AGC loop's narrow range. After setting the proper operating point with R_{21}, set the output amplitude with multiturn trim potentiometer R_7 in range of 5 Vpp to10 Vpp.Right selection of passive components in signal chain is another important requirement for minimum distortion. Resistors are preferably 0.1%, 15 ppm/K through-hole types, capacitors are preferably polystyrene

foil types, second best choice are NPO (Negative Positive Zero) with their smaller size and lower temperature coefficients, but slightly higher distortion (Ref. 6).
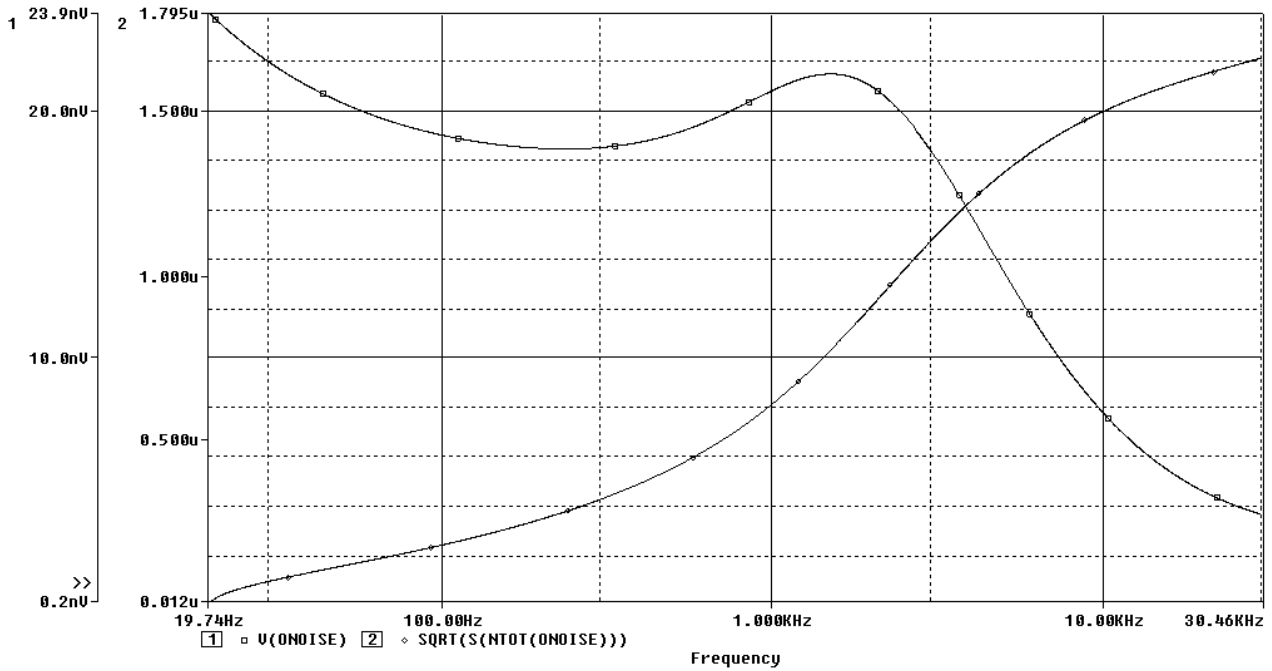

Fig. 2. Noise simulation

Performance verification

We know of no commercially available equipment with enough resolution to directly measure distortion of the ADC circuit. Fortunately, you can use a simple two-stage approach. First, attenuate the fundamental frequency as much as possible; at least 80 dB. A low-distortion notch filter lets you measure residual distortion much more simply than a spectrum analyzer. **Figure 3** shows a tunable notch filter with an amplifier. The notch filter is a passive twin-T circuit, which rejects the oscillator's fundamental frequency, but it also attenuates the second and third harmonics by about 9 dB and 5 dB, respectively.

Distortion performance of the notch filter is important, so use the same high quality passive components as in the oscillator. Feed the notch-filter's output into low-noise amplifier IC_1 with a gain of 100. Monitor the output of this amplifier with any common spectrum analyzer or with a PC sound card and frequency-analysis software. For quick self-testing of distortion and gain accuracy of the whole measurement chain, the circuit has a jumper-selectable resistive divider (R_9, R_{10}) with 70 dB attenuation.
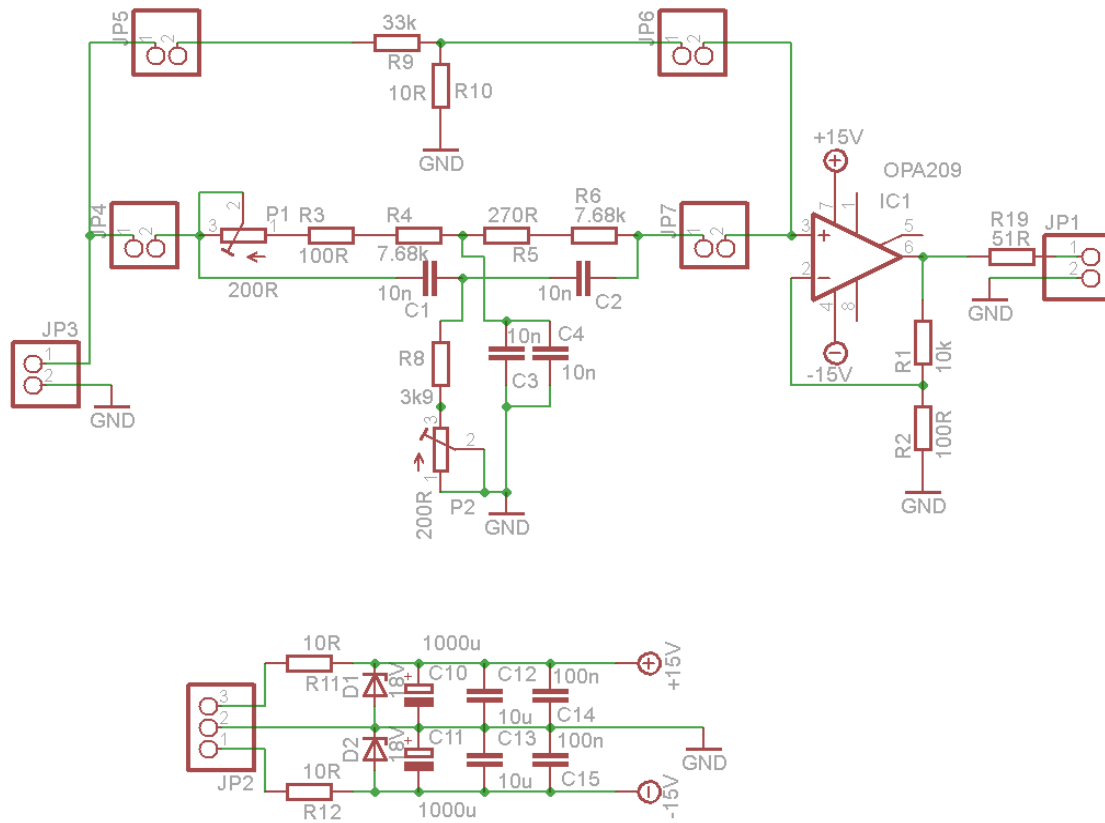
Fig. 3. Twin T notch and amplifier

Figure 4 shows the noise and distortion performance of the amplifier and analyzer together when the attenuator is connected to the output of the oscillator. We used our DAQ module AD14ETH www.janascard.cz as a spectrum analyzer. The DAQ module has a 14-bit ADC with 400 ksamples/s sample rate. The module averages 8 samples to reduce sampling speed to 50 kS/s and takes 128 ksamples to perform FFT analysis. The high number of samples is necessary for highest possible dynamic range, second harmonic is as low as –150 dBV so frequency resolution below 1 Hz is necessary. Fig. 4 shows that noise floor of the amplifier is –155 dBV. The third harmonic is –141 dBV, so the amplifier's THD together with that of DAQ module is less than 80 dB.

After verifying that JP_5, JP_6 are open and JP_4 and JP_7 are closed, connect an AC voltmeter or oscilloscope to the output and tune P_1 and P_2 for maximum attenuation of the oscillator's fundamental frequency. Now the filter is ready to measure the oscillator's THD. **Figure 5** shows distortion of the oscillator with NPO capacitors, the second harmonic is –147 dBV, the third harmonic is –143 dBV, oscillator output level is +10 dBV. Thus, the second harmonic is 10 dB+147 dB –9 dB = 148 dB below the fundamental. The third harmonic is 10 dB +143 dB –5 dB = 148 dB below the fundamental. THD is –145 dB. **Figure 6** shows distortion with C_3 replaced with a polystyrene foil capacitor. Distortion is several dB lower. The second harmonic is –151 dB, which is nearly invisible in the noise. The third harmonic is also –151 dB below the fundamental. THD is –148 dB.
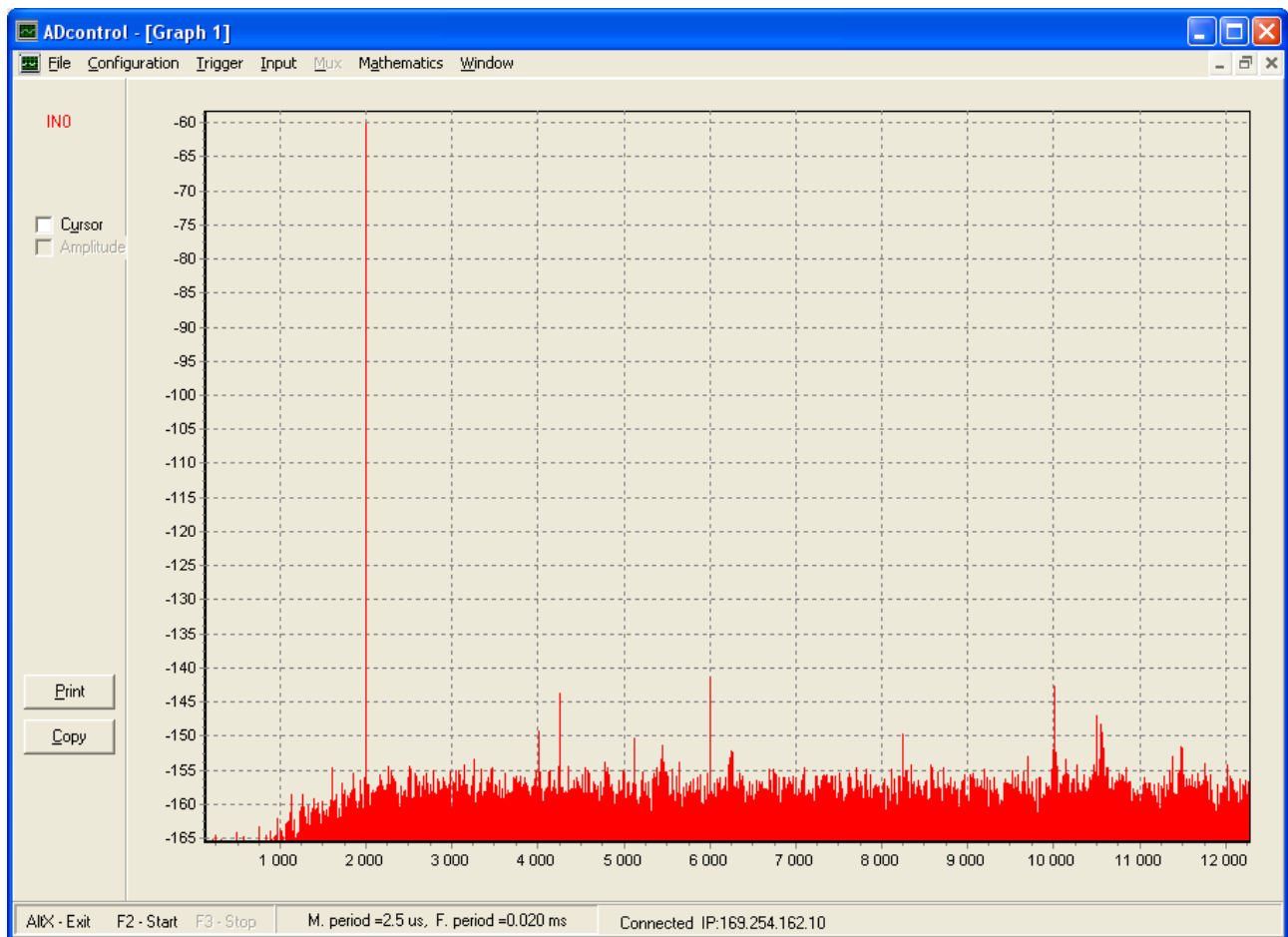
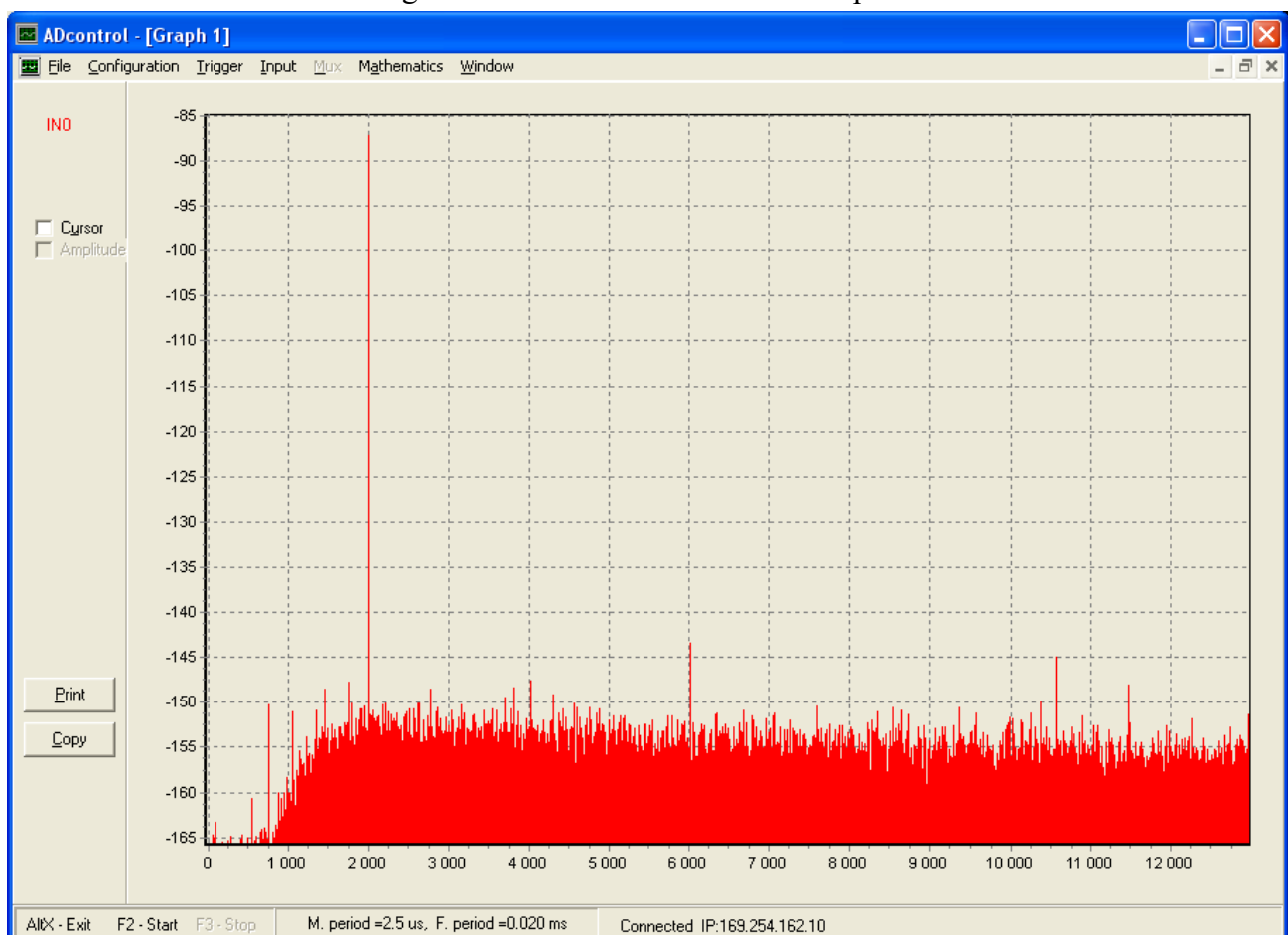Fig. 4. Noise and distortion of the amplifier

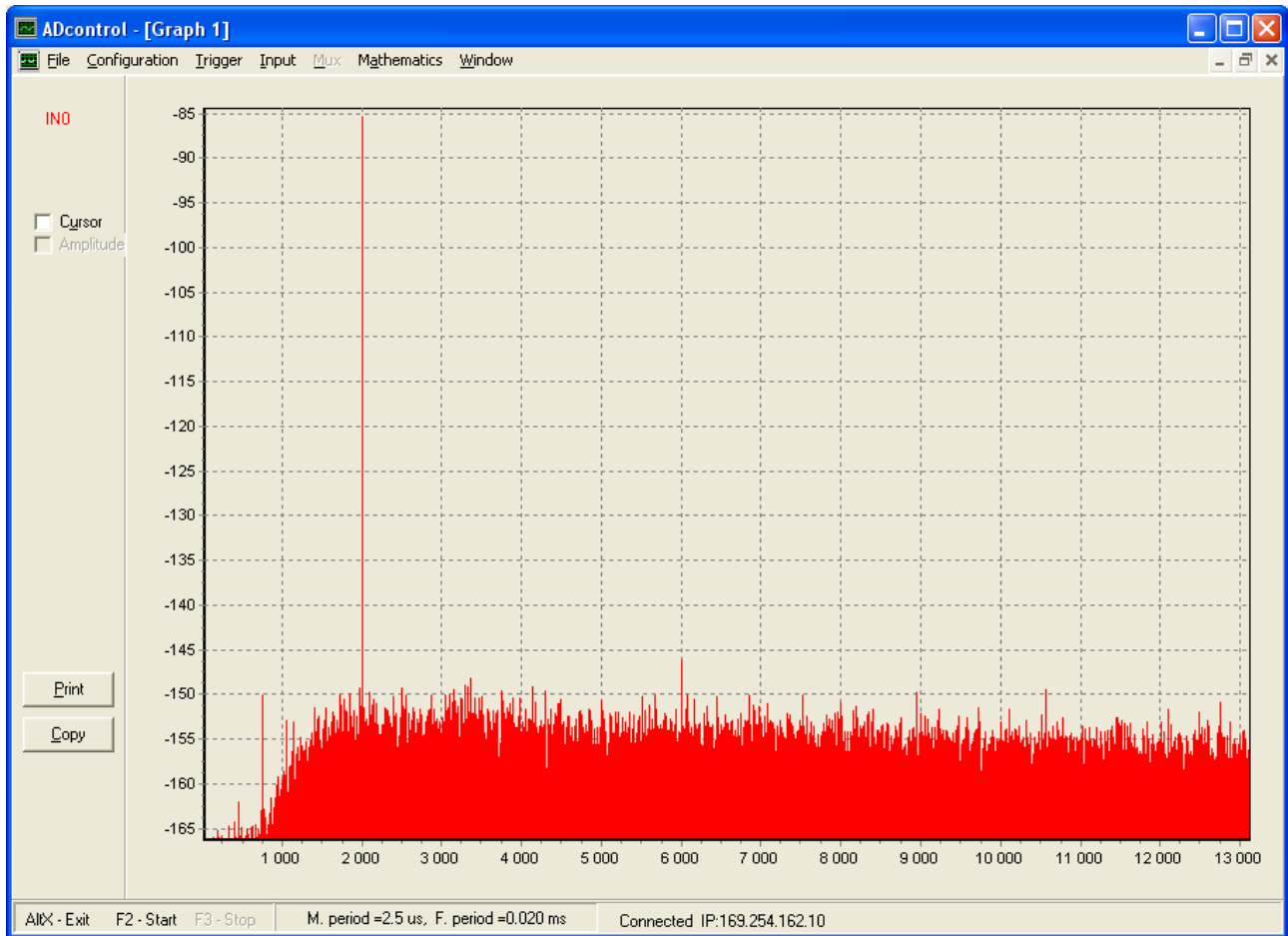Fig. 5. Distortion with NPO capacitors

Fig. 6. Distortion with polystyrene foil capacitor

When lower performance is acceptable, significantly simplified version of an oscillator can be used. The oscillator in **Figure 7** is a standard noniverting Wien bridge with gain +2 around IC_1 and integrator IC_2, active rectifier is replaced by dual diode D_5, the second half act as a temperature compensation. This simplified version has THD -120 dB and higher noise than the first circuit due to higher noise gain of the circuit and no bandpass filtering but it still outperforms many at least 100x more expensive types of equipment.

Fig. 7. A simple Wien oscillator

Actualization 9/2020

A few tens of the described oscillator with various frequencies were built during the last years, here are some experiences.

1. Although a carefully designed double-sided PCB was used, a performance of the prototype was rarely achieved, nevertheless higher harmonics was below 140 dB in most cases.

2. LME49710 became obsolete now and a new king between ultra-low distortion amplifiers OPA1656 came, so the PCB was redesigned to fit OPA1656. The datasheet of OPA1656 [7] specifies that higher harmonics are lower than 160 dB for frequencies below 2 kHz. Unfortunately, there is no description how such distortion was measured. Direct measurement (Fig.12 of the datasheet) requires a generator with distortion well below 160 dB and also an ADC with such THD, it is several orders bellow any available equipment as far as I know. I am a little bit sceptic also about the credibility of another common approach – using higher noise gain of the tested amplifier and THD measurement with a common THD meter. I think this approach works well at higher frequencies, but it is questionable at lower frequencies where a low open-loop gain of the tested OA isn't an issue and other sources of distortion especially in the input stage can play their role.

A new version of the oscillator with OPA1656 was tested at frequencies 1 kHz a 2 kHz. The same board with the same NPO capacitors was used, only frequency setting resistors R1,R2,R3,R4 were changed correspondingly. The output amplitude was 10Vpp = 3.53 VRMS = 11 dBV. The measured results are in fig. 8 and 9 and the results are slightly disappointing. They are better than a typical oscillator with LME49710, but still worse than my unusually good old prototype with LME49710. Fig. 8 shows performance at 1 kHz. The second harmonic is nearly invisible in noise – about -153 dBV = 155 dB bellow fundamental, but the 3. harmonic is -140 dBV = 146 dB bellow fundamental. The results of the 2 kHz version are shown in Fig. 9: 2. harm. -141 dBV = 143 dB bellow fundamental, 3. har. -146 dBV = 152 dB below fundamental. The results changed significantly, 2. harm is 12 dB worse, the 3. is 6 dB better. I have no explanation for such a significant difference.

Conclusion

Measured results with OPA1656 shows that a low distortion amplifier itself is only a part of the problem, used capacitors are another key component, my experience shows that NPO caps are an optimal choice, this opinion also confirms [8] with a good description of the measurement of the cap distortion. Distortion of the whole oscillator bellow 140 dB can be reached with high probability, distortion bellow 150 dB is challenging even with the best OA and verification of achieved results is always necessary.
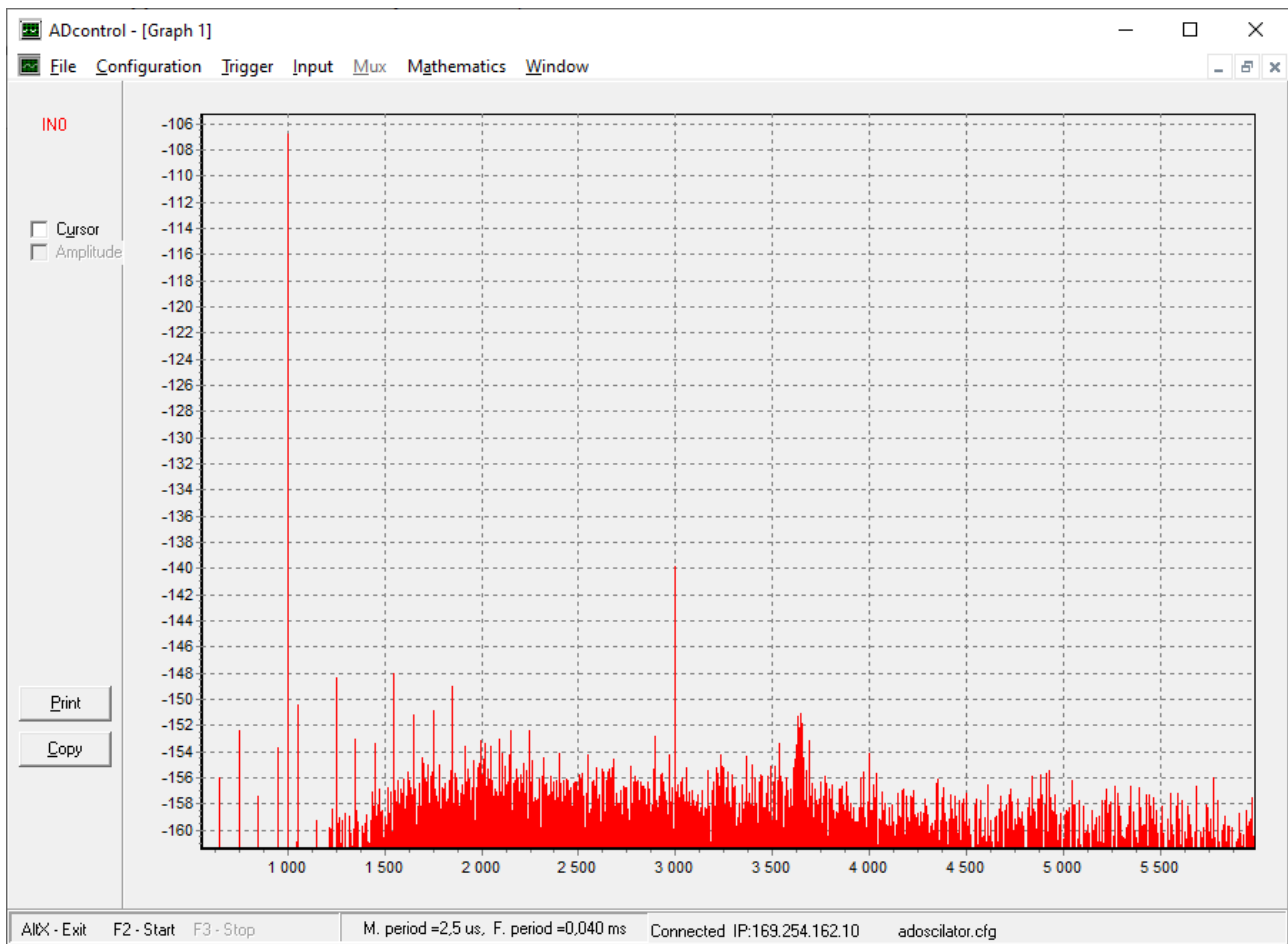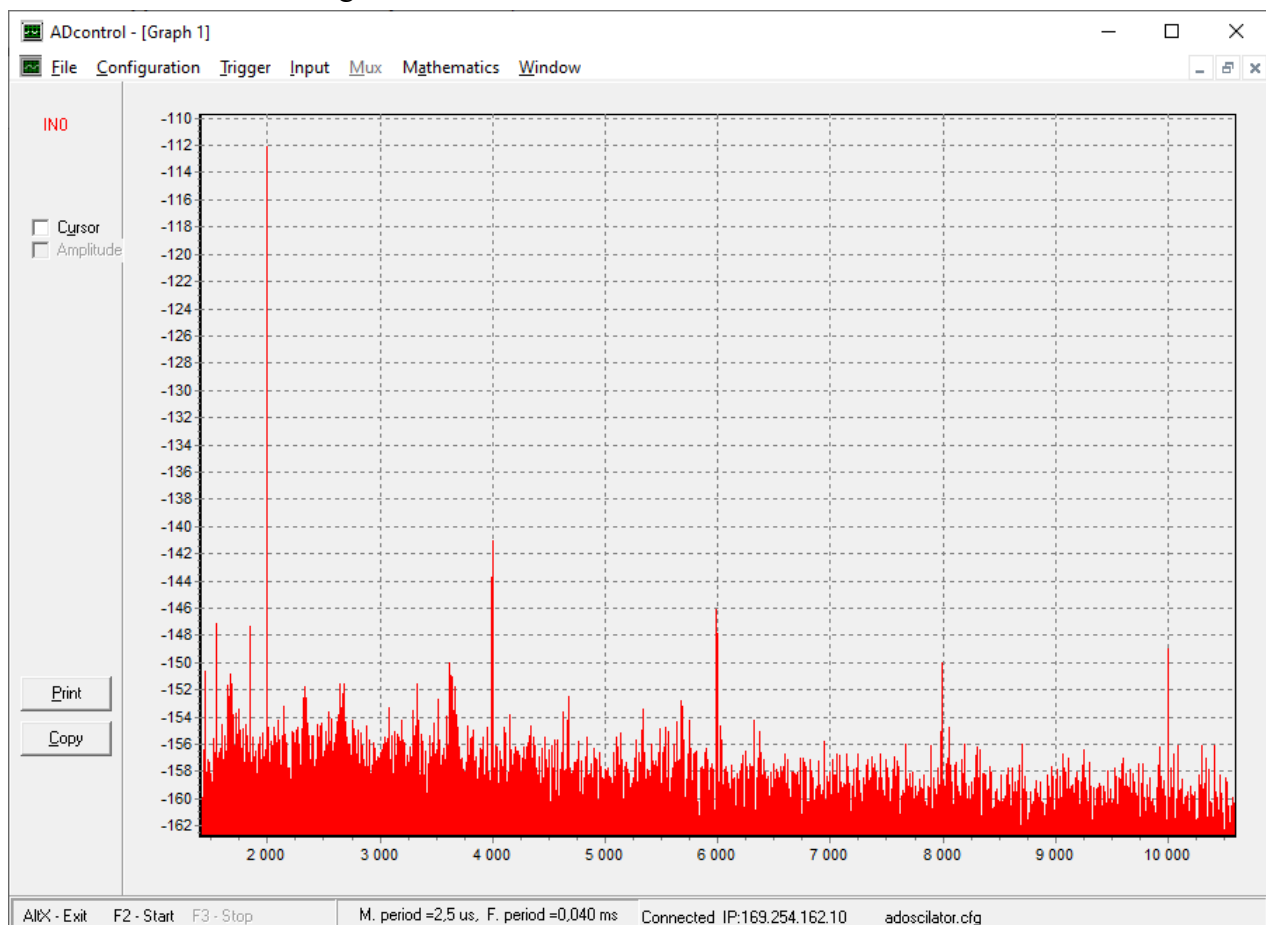
Fig. 8. Oscillator with NPO and OPA1656 at 1 kHz

Fig. 9. Oscillator with NPO and OPA1656 at 2 kHz

References:

1. Audio Precision analyzer series 2700, http://ap.com/products/2700

2. Smith, Jeff, "Oscillator keeps THD below 1 ppm," *EDN* Design Ideas, November 10, 1994. http://www.edn.com/article/497193-EDN_11_10_94_Oscillator_keeps_THD_below_1_ppm.php

3. Eagar Dale, "Using Super Op Amps to Push Technological Frontiers: an Ultra-Pure Oscillator" http://cds.linear.com/docs/Application%20Note/an67f.pdf

4. Williams, Jim and Guy Hoover, "Test 18-bit ADCs with an ultrapure sine-wave oscillator," *EDN*, August 11, 2011. http://cds.linear.com/docs/Article/ubm_edn_20110811%2018Bit%20ADCs%20Ad%20Free.pdf

5. Pease, Robert A.,"Gain and Linearity Testing for Precision Operational Amplifiers," National Semiconductor Application note 1671, May 21, 2008. http://www.ti.com/lit/an/snaa047/snaa047.pdf

6. Bateman, C.,"Capacitor Sounds 1 - Low Distortion (sub 1PPM) 1 kHz Test Oscillator"

http://www.waynekirkwood.com/Images/pdf/Cyril_Bateman/Bateman_Notes_Cap_Sound_1.pdf

7. OPA1656 data sheet, www.ti.com

8. Groner S., "Quadrature Bridge Measures Harmonic Distortion in Capacitors", Linear Audio vol.12.