Being an ardent supporter of the shunt negative feedback in audio and electronics, I would like again to demonstrate its advantages, this time on the example of the offered below oscillator. This oscillator will be explored also to learn what minimum distortion can be achieved with the amplitude stabilization system employing a single modern JFET.

So far the distortion measurements have been conducted in the interactive mode with the help of Multisim distortion analyzer performing Fourier analysis of the tested devices' outputs. But this method has two serious limitations - distortion below 0.001% can not be measured and manual setup of the distortion analyzer fundamental requires this frequency to be exactly equal to the test frequency. This condition is easily satisfied when testing amplifiers by the signal originated from the Multisim pure sine-wave generator whose frequency is set manually too.

But in the case of tested oscillators the slightest mismatch of their own frequency and the Multisim distortion analyzer setting may lead to inaccuracy in the carried out THD measurements.

Just the need to investigate the super-linear circuitry of amplifiers and oscillators has prompted me to develop the unprecedented in its reliability, accuracy and sensitivity method of measuring distortion with the help of my virtual VK-2 distortion meter. Its circuit is entered to the simulation program along with the circuit of device under test whose normalized 1V output is connected to the meter's input active rejection filter. The latter automatically tunes itself to the fundamental frequency, its more than -170dB suppression being reached in less than 3sec within 20Hz-20kHz.

Distortion residuals, amplified by +80dB, are appearing at the VK-2 distortion meter main output during the whole process of this interactive simulation, they are free of any swamping noise and any added distortion because the Multisim oscillator and the VK-2 virtual meter don't create distortion and noise by definition. It's why the measured by an ordinary RMS millivoltmeter and seen on the virtual oscilloscope screen is the distortion harmonics' sum attributed exclusively to the device under test (amplifier or oscillator), its registered value may lie between 0.01% and 0.0000003% -(80-170dB) that corresponds to the meter's main output between 1V and 30μV.

After stopping the simulation, all obtained measurement data and screenshots can be saved in a file. By the way, the screenshot of extracted output distortion superimposed to the sine-wave input signal is very helpful in understanding the cause of this distortion. For example, narrow spikes on the distortion curve at the moments of the input sinusoid zero-crossing tell about the underbiased output transistors of a power amplifier, the third harmonic of distortion tells about clipping issues, the second harmonic of an oscillator's distortion characterizes the performance of its amplitude stabilization system and so on.

The accuracy of measuring the residual distortion harmonics can be easily verified by applying their calibrated amounts, say -120dB, to the meter's input, along with a 1V signal of the fundamental frequency, and analyzing its output, this accuracy being better than 0.5dB at all audio frequencies.

Returning to the oscillator, it should be noted that its topology has a great potential of reducing distortion the sine-wave signal is produced with.
Relationships between its input $V_{IN1}$ and output $V_{OUT1}$ voltages can be written with the help of potential $V_{01}$ being equal at the inverting and non-inverting inputs of $A_1$, here $V_{01} = 0$.

$$I_{01} = \frac{V_{IN1}}{R_1}; \quad V_{OUT1} = 0 - I_{01} = \frac{1}{C_1s} V_{IN1}.$$

Similarly for the second integrator stage:

$$I_{02} = \frac{V_{OUT1}}{R_2} = \frac{V_{IN1}}{R_2 R_1 C_1 s}; \quad V_{OUT2} = 0 - I_{02} = \frac{1}{C_2 s} V_{IN1}.$$

Potential at the inverting and non-inverting inputs of $A_3$:

$$V_03 = \frac{V_{OUT1}}{R_{34} + R_{35}} = \frac{-R_{34}}{R_1 C_1 s (R_{34} + R_{35})} V_{IN1}.$$

Next we determine currents $I_{031}$ and $I_{032}$ flowing in the direction to the inverting input of $A_3$:

$$I_{031} = \frac{(V_{OUT1} - V_03)}{R_{31}} = \frac{V_{IN1}}{R_1 C_1 s (R_{34} + R_{35}) R_{31}}; \quad I_{032} = \frac{V_{OUT2} - V_03}{R_{32}} = \frac{V_{IN1}}{R_2 C_2 R_1 C_1 s^2 (R_{34} + R_{35}) R_{31} R_{32}};$$

Current flowing through resistor $R_{33}$:

$$I_{033} = I_{031} + I_{032} = \frac{(R_{34} R_{31} - R_{35} R_{32}) R_{32} C_2 s + R_{31} (R_{34} + R_{35})}{R_2 C_2 R_1 C_1 s^2 (R_{34} + R_{35}) R_{31} R_{32}} V_{IN1}.$$

The third stage output:

$$V_{OUT3} = V_03 - I_{033} R_{33} = \frac{(R_{34} R_{31} - R_{35} R_{32}) R_2 C_2 s - R_{31} (R_{34} + R_{35})}{R_2 C_2 R_1 C_1 s^2 (R_{34} + R_{35}) R_{31} R_{32}} V_{IN1}.$$

The circuit will oscillate if all its three stages are connected in the closed loop, i.e. $V_{OUT3} = V_{IN1}$ and the above expression equals to unity. This expression can be represented in the frequency domain after the replacement $s = j\omega$.

$$(-R_{34} R_{31} R_{32} - R_{35} R_{32} R_{33} + R_{35} R_{32} R_{33}) j\omega R_2 C_2 - R_{31} R_{33} (R_{34} + R_{35})$$

$$-R_2 C_2 R_1 C_1 \omega^2 (R_{34} + R_{35}) R_{31} R_{32} = 1.$$

The oscillation frequency is defined as $\omega_0 = 1/\sqrt{R_2 C_2 R_1 C_1}$, usually the parameters of both integrator stages being chosen identical ($R_1 = R_2 = R$; $C_1 = C_2 = C$), therefore $\omega_0 = 1/RC$.

Further simplification comes if we assume $R_{32} = R_{33}$, that yields the final condition of appearing the sine-wave generation:

$$\frac{(R_{35} R_{33} - 2 R_2 R_{31}) (\omega/\omega_0) - R_{31} (R_{34} + R_{35})}{(R_{34} + R_{35}) R_{31} (\omega/\omega_0)^2} = 1.$$

This condition will be satisfied at the oscillation frequency $\omega = \omega_0 = 1/RC$, if $R_{35} R_{33} - 2 R_2 R_{31} = 0$. (1)

At the oscillation frequency the outputs of all stages are equal in magnitude but different in phase – the integrators provide a 90° phase shift between input and output, while the third stage operates as an inverter to restore the phase 360° balance within the closed oscillating loop.

The choice of component values is an important moment in practical implementation of this oscillator. For the oscillation frequency of 1kHz most typical capacitor value is $C_1 = C_2 = C = 16nF$, with resistor value $R_1 = R_2 = R = 10k\Omega$ it gives exactly 994.7Hz. I don’t consider here the oscillator noise performance which can be improved by reducing the circuit resistors’ values, therefore I think the optimum value for the frequency setting resistors might be $R_1 = R_2 = 3k\Omega$.
The circuit fragment adjoining to the non-inverting input of inverter $A_3$ is a voltage divider $R_{35} - R_{34}$, the latter resistance containing an amplitude regulating element (JFET) being in principle non-linear. Negative effect of this non-linearity can be minimized when choosing a less than 15mV voltage drop across the JFET on-resistance which is set within 100-150Ω. Given that the typical oscillator output is 2V, the above condition will be met if $R_{35} + R_{34} = 20-30k\Omega$.

Also, resistance $R_{35}$ must be much greater than $R_{34}$ to keep the input potential of op amp $A_3$ as low as possible for reducing the common-mode distortion produced by this stage. By taking $R_{35} = 27k\Omega$ and $R_{35} / R_{34} = 20$, the resistance $R_{34}$ will be 1.35kΩ, it represents the series connection of a 1.2kΩ metal-film constant resistor and a 2N4391 JFET with its about 150Ω on-resistance. After specifying $R_{32} = R_{33} = 10k\Omega$, the last unknown resistor value ($R_{31}$) can be found from the main condition of appearing the oscillation (1). It is $R_{31} = 100k\Omega$.

The first full oscillator circuit is depicted in Fig.2. I use here the typical amplitude stabilization system containing a full-wave rectifier (op amps $U_5$, $U_7$), a reference voltage producer ($D_8$, $R_{92}$) and output filter (op amp $U_6$) which compares the oscillator rectified output with the reference and forms a control voltage for the regulating JFET to initiate and sustain the oscillation at a certain frequency and with the required amplitude. The oscillator’s 2V RMS output is typical too, it’s the result of compromise between low distortion and low noise, both factors being equally important when designing ultra-low distortion oscillators.

![Fig.2. State-variable oscillator (op-amplifier version).](image)

There are three main sources of distortion in this oscillator. The first is its oscillating loop consisting of the string of operational amplifiers, whether they are integral devices or composed from discrete components. When using modern high-performance op amplifiers with the claimed produced distortion of less than -130dB (AD797, LME49710, LM4562, OPA134), it’s reasonable to expect the same distortion performance and from the oscillator. Unfortunately, I can not check that with the help of my virtual VK-2 distortion meter which is unable to directly evaluate the op amplifiers distortion because their simulation models simply don’t contain the corresponding data and they therefore exhibit infinite linearity. In our case, this fact is rather positive and allows to evaluate more correctly the distortion contributed by the JFET and amplitude stabilization system.

As for the used LT1115CN8 op amplifiers, they behave very well in simulation, demonstrate realistic output voltage clipping when the input is badly overloaded, and their model characteristics are close to the real parameters. To reliably determine their distortion, the LT1115CN8 full circuit diagram should be entered into the simulation program and analysed then by the VK-2 meter. Some of the super-linear op amplifiers have been already tested in this way and the results are very interesting.

I use in this oscillator a 2N4391 JFET transistor, the biasing voltage at its gate is established about -4.5V to get its drain to source on-resistance of 100-150Ω for better linearity, the latter being also enhanced by the AC feedback via a $R_{10} - C_{09}$ network.

The third source of distortion is associated with the regulating JFET too, the control voltage applied to its gate is modulated by the double-frequency ripple left from non-ideal filtering of the full-wave rectifier output, this modulates, for its turn, the JFET on-resistance and leads to increasing the second harmonic of oscillator distortion. The filtering here is carried out by the first preliminary low-pass stage ($R_{174} - C_{70}$) and the second main stage ($R_{95} - C_{44}$) including the $U_6$ op amplifier. The choice of filter components is very critical, as it’s responsible also for the amplitude settling process which
ideally might be fast aperiodic. The compromise between good filtering (low distortion) and good amplitude stability can be found, but only in a narrow frequency range or at fixed frequencies.

The worst situation is when the amplitude settling process cannot all be finished successfully. After power is applied to the oscillator circuit, its amplitude starts to increase from zero thanks to the JFET minimum on-resistance provided by zero and even positive (to 0.6V) biasing potential formed by the U6 op amplifier output. The growing and rectified oscillator output is applied in positive polarity to the U6 inverting input, trying to balance the reference negative voltage set by zener diode D8 and resistor R92. The U6 output tends to be more negative to reach the -4.5V biasing voltage necessary for the JFET to set the required 2V oscillator output and introduce the voltage balance at the U6 inverting input.

Unfortunately, the charging capacitors C70, C44 create a time delay between the above two events, the oscillator output amplitude is passing the reference voltage point and is rushing to its maximum. After a certain pause, the whole process is running in the reverse sequence. To damp this non-stop amplitude swinging from minimum to maximum and vice versa, a circuit fragment containing transistor Q58 is added. The base potential of this transistor is chosen to initiate its turning on when the oscillator amplitude exceeds 4V. After that, the recharging of C44 takes place through a much lower R176 resistance, the U6 op amplifier output quickly reaches the value making the JFET to increase its on-resistance that leads then to reducing and aperiodic settling the oscillator output at the 2V level. This process is illustrated in Fig.3 by the oscilloscope screenshot, the instrument being connected to the oscillator output. The settling time is less than 3sec.

![Oscilloscope screenshot](image)

**Fig.3.** Settling process of the oscillator 2V-994Hz output.

Now, when the oscillator circuit is described and all its components are specified, it’s time to conduct most important experiment on it – to learn exactly what level of distortion this state-variable oscillator might guarantee. The corresponding test scheme is depicted in Fig.4 where the VK-2 distortion meter is represented as an active rejection filter subcircuit block followed by the output amplifier with the gain of 100 and with the ability to normally operate in conditions of deep clipping. The rejection filter consists of an input twin-T notch network, a high-performance discrete amplifier (K=100), a 100kHz low-pass filter and at last the system of fine automatic tuning of the rejection filter, its Q-factor is chosen Q=2 and it carries out more than -170dB suppression of the fundamental frequency within 20Hz-20kHz. The extracted distortion appears at the meter’s main output as a RMS voltage reading which, being divided by 10000 (total gain) and by the normalized 1V input signal, gives this signal distortion directly in percents. The connected to the VK-2 output oscilloscope monitors the whole process of settling the oscillator amplitude and measuring its distortion.

Simulation of the oscillator circuit continues until the minimum settled readings of the output voltage measurement probe and the connected dB-meter are obtained. As can be seen in Fig.4, this procedure takes 3.27sec and yields a stunning result indeed – 830μV RMS output that corresponds to the input signal distortion of 830μV/10000=83nV or 0.0000083% (-141.6dB) relative to the 1V input. However, it should be remembered that this distortion doesn’t include
distortion of the op amplifiers the oscillator consists of. According to the LT1115CN8 device datasheet, it features THD of about 0.0005% (-106dB) in an amplifier with the gain of -10 and the 7V-1kHz output applied to a 600Ω load. With the unity gain this figure may be reduced to -126dB, but more accurate results can be obtained in the course of real experiments.

A remarkable property of this type of oscillator is that its integrator stages act as low-pass filters for distortion being the sum of the second, third and other harmonics of the fundamental oscillating frequency. Given that the lion's share of this distortion is produced by the third, inverting oscillator stage, its maximum suppression after passing the two filters will be registered at the second integrator output, just what has been measured with the help of the VK-2 meter.

Fig.4. VK-2 distortion measurement of the state-variable oscillator at 1kHz (second output).
Connecting the distortion meter to the third stage output brings a disappointing result – 0.000047%THD (-126.5dB), this is shown in Fig.5 where the third distortion harmonic is prevailing, while in the previous case it is attenuated by the filters more effectively than the second and it isn’t almost seen on the screen.

![State-variable audio oscillator schematic](image)

![VK-2 distortion meter schematic](image)

To retune the oscillator for generation at 16kHz, the capacitor value of its integrator stages should be reduced to 1nF. Again, an optimum of the amplitude stabilization system parameters should be found, this time by reducing the value of filtering capacitor $C_{44}$ proportionally to increasing the oscillation frequency, with $C_{44} = 22\text{nF}$ the system exhibits the satisfactory amplitude settling and keeps the oscillator distortion at a very low level.

This level is evaluated when simulating the oscillator circuit together with the virtual VK-2 distortion meter whose input twin-T notch network is set now to automatically operate in the 16kHz frequency range (see Fig.6).
This simulation takes 1.5sec of real time, but for a computer user it continues more than 50min for the 16kHz frequency (10-15min for 1kHz). During this time you can comfortably watch the whole process of settling the oscillation and tuning the notch filter in detail. All takes place as in the slowed video, every nuance of extracting distortion harmonics from the set normalized 1V RMS input signal is seen on the oscilloscope screen and saved in a file. The measurement probes placed at some points of the circuit monitor the simulation process at these points and give detailed time-varying information about its main parameters (voltage, current, frequency).

![State-variable Audio Oscillator and VK-2 Distortion Meter Diagram](image)

**Fig.6. VK-2 distortion measurement of the state-variable oscillator at 16kHz.**

The distortion measurement result at the oscillation frequency of 16kHz (exactly 15898Hz) is 1.41mV RMS, distortion of the VK-2 input 1V signal equals 1.41mV/10000=122nV or 0.000014% (-137dB) relatively to this 1V. I am less optimistic about distortion contribution of LT1115CN8 op amplifiers at this frequency in comparison with their contribution at 1kHz,
the correct check of the op amplifier linearity might be possible only in real tests.

To complete this oscillator study and obtain its final full distortion data, I would like to consider its circuitry built on my discrete differential amplifiers (see Fig.7). This amplifier is described in detail in the application notes section of my site www.vkaudiotest.co.uk, here I adduce only its distortion measured with the help of the VK-2 meter. Being used in its inverting configuration with the gain of K=−1 and output 2V voltage applied to a 380Ω load, this amplifier features THD of 0.0000018% (-155dB) at 1kHz and 0.0000022% (-153dB) at 16kHz, slightly lower (by some dB) distortion figures exhibits only the discrete op amplifier proposed by Samuel Groner and used in his audio oscillator.

Fig.7. State-variable oscillator (discrete amplifier version).

Fig.8. VK-2 distortion measurement of the discrete state-variable oscillator at 1kHz.
The discrete amplifier I use here operates in pure class-A, it has a 100dB open-loop gain even at frequencies up to 100kHz, nevertheless it remains absolutely HF stable with any, up to unity, feedback factor. All this explains the amplifier excellent ability to keep distortion equally low in the whole audio range and with the output loads down to 300Ω.

Simulation of the discrete state-variable oscillator discovers practically the same distortion which was registered in its version with non-distorting op amplifiers. Now, at 1kHz, we have the VK-2 meter output reading of 760μV RMS that corresponds to the input signal distortion of 760μV/10000=76nV or 0.0000076% (-141.8dB) relative to the 1V input (see Fig.8). This means that distortion produced by the discrete amplifiers is negligible in comparison with the distortion contribution of the regulating JFET and amplitude control voltage ripple.

The discrete oscillator demonstrates the same high performance and at 16kHz, its distortion measured by the virtual VK-2 meter doesn’t exceed -140dB, as shown in Fig.9. The used measurement method is transparent and very accurate, the above distortion figures will be guaranteed and in the really built oscillator prototype. Implementing it on integral op amplifiers may be simpler but makes the perspective of getting such low real distortion vague, particularly at highest audio frequencies.

![Fig.9. VK-2 distortion measurement of the discrete state-variable oscillator at 16kHz.](image)

Very interesting test is carried out at the low audio frequency – 62.2Hz, the corresponding frequency range is chosen in the input twin-T notch network of the VK-2 rejection filter. Then the value of the filtering capacitor C44 should be proportionally increased from 330nF at 1kHz to 4.7μF at 62.2Hz, also a bigger capacitance of the damping network C75–R165 is needed to keep the process of settling the oscillator amplitude close to its optimum (C75 =22μF). Due to the increased capacitance values, this process requires a considerable time which is an inevitable payment for good filtering and reaching very low distortion at 62.2Hz.

After 23.4sec from the start of simulation, the VK-2 distortion meter registers output distortion of 3.6mV RMS. Distortion of the VK-2 input 1V signal equals 3.6mV/10000=360nV or 0.000036% (-129dB) relatively to this 1V (see Fig.10).

Further development of this oscillator is focused on making its amplitude stabilization system more effective in the whole 20Hz-20kHz range, particularly at lowest audio frequencies. Implementation of the oscillator two-channel amplitude control, dynamic and precision, has proved to be the best way to resolving the contradiction between the oscillation better stability and its lower distortion. This will be considered in the subsequent articles.
As for distortion, the use of a single JFET as the amplitude regulating element puts a certain limitation on reaching distortion below the -140dB threshold. This limitation is easily seen from the last tests where all three distortion components are presented in full degree, the smallest of them, below -150dB, is caused by the non-linearity of the discrete amplifiers the oscillating loop consists of.

The JFET is responsible for the next distortion component which in simulation can be avoided at all after replacing the JFET with a non-distorting optocoupler NSL32SR3, I mean the device whose simulation model contains only its input-output characteristic without any distortion data.

The obtained oscillator circuit is depicted in Fig.11, all parameters of the amplitude stabilization system are kept intact. The distortion test is conducted at 1kHz frequency, it lasts 3.2sec and yields a 210mV RMS result that corresponds to the input signal distortion of 210μV/10000=21nV or 0.0000021% (-153.4dB) relative to the 1V input (see Fig.11).

The main conclusion from this experiment is that filtering of the detected oscillator output is effective enough to produce the amplitude stabilization system's control voltage with minimum ripple, this remaining ripple doesn't create distortion higher than -150dB. Therefore, the measured earlier distortion about -140dB is attributed just to the amplitude regulating JFET 2N4391 whose simulation model should be maximally accurate and reliable.

Real optocoupler NSL32SR3 may be able to reach lower distortion than the above JFET, nevertheless the necessary for that reducing its cell resistance and hence the voltage drop shouldn't be undertaken at the expense of losing the oscillator amplitude stability.
In conclusion, some words about the simulation method which makes it possible to freely handle vanishingly small distortion and not to fall into guessing about its real magnitude. I would like to represent in Fig.12 the circuit diagram of the active rejection filter being the “heart” of the VK-2 distortion meter. In all distortion measurement schemes this filter is shown as a subcircuit rectangle, but its functional capability is great indeed. In this study, extracting the oscillator distortion within 0.00001-0.0001% is too easy exercise for this device, it handles as well distortion down to 0.0000003% (-170dB). Availability of the VK-2 meter is particularly important for virtual testing the ultra-low distortion oscillators, because other methods and instruments for doing interactive measurements below 0.002% THD simply don’t exist.
Fig.12. VK-2 rejection filter (1kHz setting).