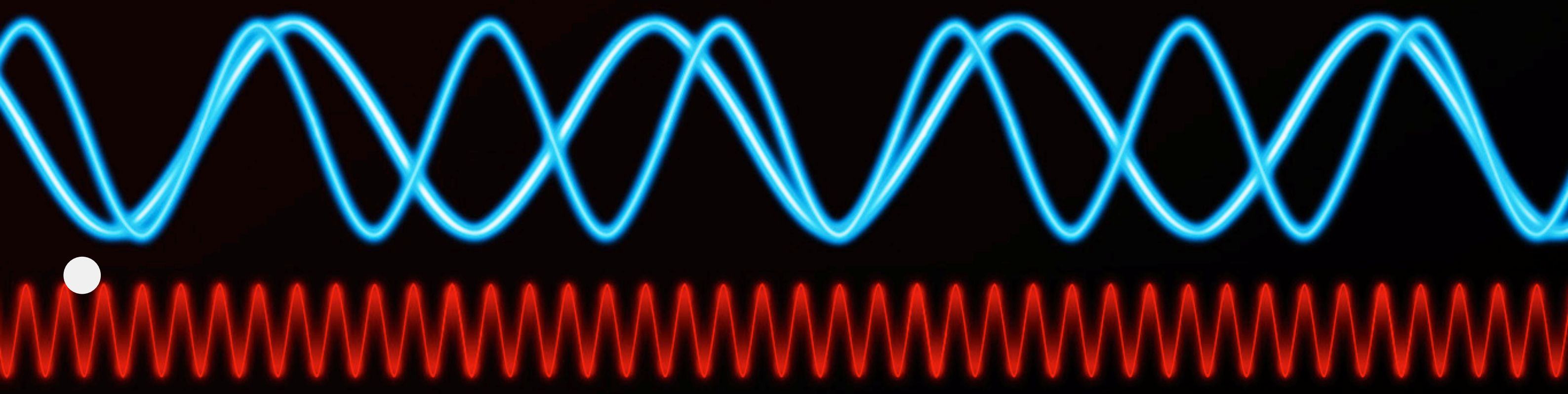
Reference Sine Wave Generator



How do you build a generator using only a few components while obtaining the lowest possible distortion? Here follows the account of the practical experience from many experiments, which resulted in a state-variable oscillator with a distortion well below 0.001%.

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When measuring, calibrating and testing of audio (test) equipment the availability of a test oscillator, which is capable of generating a sine wave (of 1 kHz, for example) that is as pure and low distortion as possible, is practically indispensable. These days, an obvious solution would be to use the sound card of a PC as a sine wave generator. In conjunction with one of the many available (freeware) programs it is very easy to obtain a defined sine wave from the DAC in the sound card. If, however, we take a close look at the specifications of a good sound card (even including those with 24-bit resolution) then the specified values for distortion will be somewhat disappointing. Even a more expensive card or (even better) an external sound adapter which is connected via USB, generates signals with a THD somewhere between 0.01% (–80 dB) and 0.003% (–90 dB). The aforementioned THD number gives the ratio between the voltage of the sine wave signal (the fundamental) and all other noise components. These noise components include harmonics, random noise and non-harmonic whistles and beeps. In practice it turns out that the distortion at the output of a sound card is often the result of all kinds of interference products which appear in the audio bandwidth. In any case, my hobby PCs (a desktop and two old laptops) with built-in sound cards were all unsuitable for generating something that looked like a clean signal.

Low distortion with few components

Would it be possible the build a sine wave generator, using only a few components, which provides a much better performance? A generator that can produce a signal with a distortion in the region of 0.001% (–100 dB) or lower, that would be very nice. A sine wave signal with such a low distortion would be a very usable reference signal, certainly for the audio measurements that I had in mind. Because there are plenty of Elektor readers who are also keen to experiment with analog circuits, I would like to elaborate about the circuits and designs you are likely to encounter during your quest. There is, after all, a certain charm to assemble a few components, without getting involved with firmware or software, and have something functional in your hands.

And for test equipment it remains downright convenient to have a standalone device which will work by itself, without having to drag along a PC as well.
The challenge for me was to build a sine wave generator that could be easily copied by others, uses only a minimal number of components and has a low cost. Oh yes, and also requires no calibration. The aforementioned desire to obtain a distortion below 0.001% (–100 dB) is, of course, also still standing.
If our preference is for a design with a minimum number of components, then a natural first attempt is to start with a classical Wien bridge oscillator. Much useful information about this can be found in an application note from the company Linear Technology, written by Jim Williams [1]. This contains a few examples of oscillators with a Wien bridge. In its simplest form, in addition to the Wien bridge, there is an opamp as amplifier, while an ordinary incandescent light bulb serves as amplitude stabilizer. A light bulb in a modern electronic circuit? This is perhaps not so strange when you realize that an incandescent lamp effectively operates as a voltage-dependent resistor. By using the properties of the filament we obtain a simple form of amplitude control. After all, the higher the voltage across the lamp, the higher the dissipation, and that means a higher temperature of the filament. Just like most other metals, the resistance of the tungsten from which the filament is made has a positive temperature coefficient: A higher temperature results in a higher resistance of the wire. The filament therefore behaves like a PTC-resistor. By including the incandescent lamp in a feedback circuit a controller can be realized which will reduce the gain when the amplitude of the sine wave signal increases. When the closed-loop gain becomes less than 1, then amplitude will reduce again. After some time, a steady-state will be reached at a certain amplitude. In this way the amplifier is prevented from limiting itself. This limiting action would otherwise result in a distortion level that is unacceptably high.

In the story from Linear Technology even the simplest Wien bridge oscillator already generates a signal with a distortion (THD) of only 0.0025% (–92 dB). Not bad at all! This distortion is mostly generated by the lamp. This is because of the fact that the dissipation in the lamp varies during the period of the sine wave. This therefore varies the temperature of the filament in time with the sine wave and therefore also the resistance of the wire. The result is a distortion which predominantly contains a third-order component. The amount of this distortion also depends on the thermal inertia ('slowness') of the filament. This is, among other things, also dependent on the (average) temperature of the filament. It is difficult, if not impossible, to establish the exact amount of distortion that will result beforehand. This will therefore have to be established experimentally.
In practice this means an acceptable compromise has to be reached between the amount of distortion, speed of the control loop and amplitude stability.

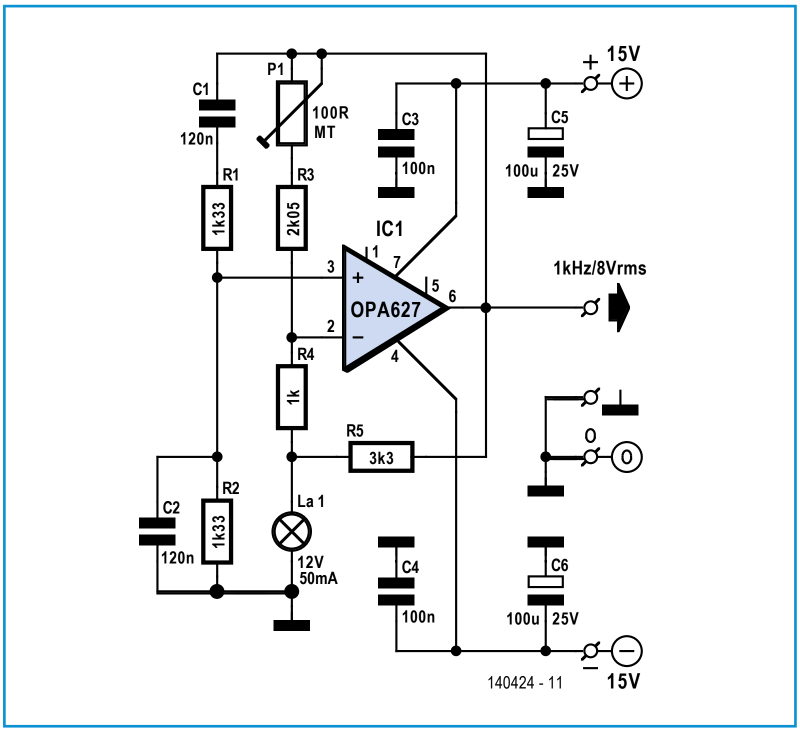

Figure 1.
1000-Hz sine wave generator from Elektor 12-94

Sine wave generator

If we prefer a low distortion at the expense of amplitude stability, then with a few more components we can retrieve a previous Elektor design: A simple sine wave oscillator was already described in Elektor some 20 (!) years ago [2]. The opamp used in

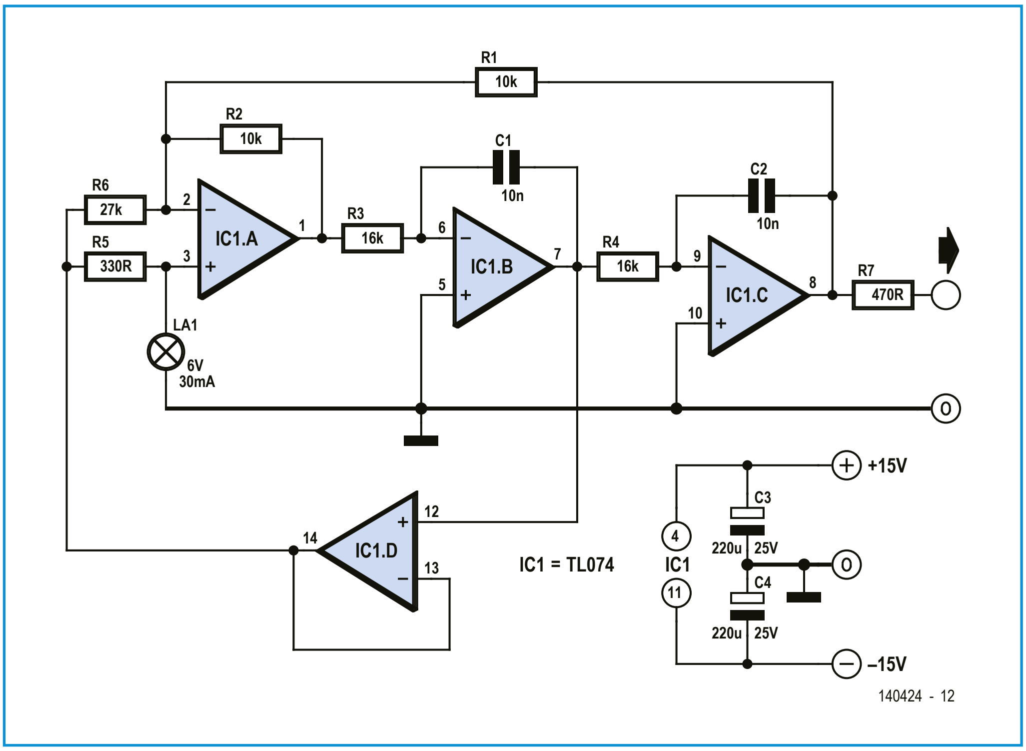

Figure 2.
State-variable sine wave generator with a lamp as stabilization element.

this design (see **Figure 1**) costs more than € 20 these days; that is why I first tried to build the sine wave generator with a cheaper opamp, as was already suggested in the original article.
The results were not disappointing: with one of the two opamps in a TL082 a THD of –96 dB was obtained and with a NE5532 I even reached –105 dB. Perfectly suitable for me. But it was, however, not all that straightforward: the low distortion value was only obtained after some experimenting. The component selection appears to be very critical and also the calibration of the amplitude has to be very precise. It is very difficult to 'tame' the amplitude of the oscillator in this design. When the ambient temperature increases the amplitude also decreases quickly. This is to be expected, because the operating point of the oscillator is such that the temperature of the filament is very low. This means that variations in the ambient temperature have a significant effect on the output amplitude.

State-variable oscillator

In spite of all this I was keen to continue experimenting, with the objective of finding a circuit that is less sensitive to component values and has a more stable output amplitude. There are various alternatives to the incandescent lamp as amplitude regulator in the form of JFETs and opto-couplers, for example. A number of these can be found in the aforementioned story from Linear Technology. Some — a trade-off with simplicity. And if you then also have to use expensive or critical components then we will have missed our design goal.
So, the circuit with the lamp is and remains a great starting point. You could, for example, start with the Wien bridge oscillator (with lamp) and follow it with a simple band-pass filter or low-pass filter to suppress the harmonics. This could be built very easily using a dual opamp.
Continuing with the possibility of building an oscillator followed by a harmonic filter, I arrived at an oscillator type that effectively has the filter built in: the 'state-variable' oscillator. This type of oscillator was often used, among other things, in professional audio test equipment before digital techniques became commonplace. Strange enough, I never came across such an oscillator that uses a lamp as its stabilizing element. So it is of course interesting to quickly try out such a lamp-circuit on a breadboard. With surprisingly good first

results!
Now such a state-variable oscillator has the disadvantage that it requires at least 3 opamps. But when we realize however, that 4 opamps in a 14-pin IC are readily available and relatively inexpensive then we can easily overlook this.
The circuit is reproduced in **Figure 2**. At first glance the circuit is much more complicated compared to the Wien bridge oscillator. And sure enough, four opamps were used. But it is then funny to observe that the actual number of components used are not all that many more than the simple Wien bridge oscillator. The design consists of a single IC and 12 passive components. This is comparable to the sine wave generator from **Figure 1**. As you can see, the heart of the circuit consists of a quad opamp type TL074. This IC is proof that an ancient opamp design such as this can still stand its ground among all that modern opamp stuff. And all that for a laughably low price. So it is not surprising that this IC is on the Elektor list of preferred components...
The state-variable oscillator consists of two integrators, in this case IC1.B and IC1.C with the accompanying RC-networks R3/C1 and R4/C2. These two integrators, one after the other, result in a phase shift of 180º. An inverting amplifier with a gain of -1 (IC1.A with R1 and R2) also gives a phase shift of 180º. Together with the integrators this results in a total phase shift of 0º. When we connect all this in a loop, all the conditions for an oscillator are met when the loop gain is equal to 1. When the inverting amplifier has a gain of -1, then the oscillator frequency is:

$f_0 = 1 / (2\pi RC)$
where: R = R3 = R4 and C = C1 = C2

In theory we now have an oscillator already. To get it started and for amplitude regulation we require the circuit with the lamp. This effectively consists of a bridge circuit with R5 and the lamp in one leg, and R6 and R1 in parallel with R2 in the other. The signal for this bridge comes from the first integrator. This signal has a phase that is shifted 90º with respect to the input of the inverting amplifier. Now the trick is that the difference voltage of the bridge will change the phase shift of the inverting stage. The lamp circuit therefore does not regulate the loop gain, but regulates the phase instead. An additional advantage is that the components in the bridge circuit have no influence on the oscillator frequency.
At the selected operating point of the lamp, the output of the opamp has to supply about 7.5 mA of current. One section of the TL074 opamp can easily do this, but that does result in increased distortion. That is why the fourth and final opamp section of the TL074 is used here to generate the signal to the bridge with the lamp. When the bridge is in equilibrium (which is the case when the amplitude is stable) then the distortion in this opamp is nicely eliminated in the remaining signal path. Unfortunately, the distortion caused by the lamp is entirely present at the output of gain stage IC1.A. But fortunately the two integrators operate as a low-pass filter. This suppresses harmonic distortion and also reduces (broadband) noise. That is also the reason that the output signal is taken after the second integrator: at this point the distortion is the lowest! More information about all kinds of distortion-free oscillators, and the state-variable in particular, can be found on various internet sites [3], [4] and [5].

Component selection
Concerning the lamp that was used: I had as a design requirement a type of lamp that would be readily available. The choice was made for a so-called ‘wedge base bulb’ of 6 V/30 mA. With this type you can easily bend the contact wires away from the fitting, after which you can simply solder the lamp into the circuit board. These lamps are available from several suppliers; I simply bought mine from my local parts supplier. Incidentally, various other types of lamps are also suitable. More about that later.
The first experiments were done with components I had on hand: so initially ordinary carbon resistors were used and capacitors C1 and C2 were MKT (polyester) types. The distortion is then already well below −100 dB. A low distortion is therefore easily obtained with cheap, standard components! Because of the large tolerance of these parts, the oscillator frequency can deviate

Potential interference sources

Here are a few tips in the event of problems. With these it is important that you can see what the nature of the distortion is. Most distortion meters have an output for this, where you can display the residual (everything except the fundamental) on an oscilloscope.

- **Hum**: This can be caused by electrical coupling. In this case it will help if the circuit is shielded. If that doesn't solve the problem then the cause is probably a ground loop: first of all it is very important to look at the power supply. The output from the power supply must not be connected directly to the protective earth of the wall socket. If that is unavoidable, then insert 3 resistors of 47 Ω in series with the three wires from the output of the power supply. In addition, it may be necessary to connect only one (test) instrument at a time. So, when you connect the distortion meter, then disconnect the oscilloscope (including the earth clip!).

- Strange 'lurches' and a relatively high frequency AC signal in the residual can be a sign of **instability**. Although the TL074 is a reasonable 'tame' opamp the whole thing can become unstable of the decoupling electrolytic capacitors are too far away from the opamp. The electrolytics also need to be of good quality (low ESR). When in doubt, a smaller capacitor of, for example, 100 nF can be connected in parallel with each electrolytic. Also avoid long wires and in particular keep the ground line short and neat. Also keep in mind potential interference from nearby radio transmitters. Shielding is necessary if this is a problem for you.

- **Noise**: This can be caused by noise on the power supply lines, generated by the power supply. In this case it can help to insert two resistors of, for example, 47 Ω in series with each of the power supply lines. Also note the quality of the electrolytic capacitors.

considerably from 1 kHz. In addition this frequency is quite dependent on ambient temperature. For the capacitors I finally settled on affordable polypropylene film capacitors from the FKP-2 series made by Wima, which have a tolerance of 2.5%. If all the resistors are 1% metal-film types then the output frequency will be 1 kHz with a deviation of at most a few tens of Hertz. The output frequency remains stable with varying temperature, also changes in the (bridge) circuit near the lamp do not show up as changes in frequency. If you nevertheless prefer to adjust the frequency to exactly 1 kHz, then you can, for example, fit a 25-turn trimpot of 500 Ω between R1 and R2. The wiper of the potentiometer is then connected to the inverting input of IC1.A.
To test the reliability of duplicating the circuit, I tried three different lamps in the circuit. The amplitude at the output is, depending in the lamp tested, between 2.81 and 3.14 V. This spread is not a cause for concern; in fact this is to be expected when considering the tolerance of the resistance of the lamps. The resistance values of R5 and R6 are not critical either, you can use carbon resistors for these. I also tried different TL074-ICs, made by TI and STS, but I could not discern any difference. I then did tests to determine the sensitivity to power supply voltage variations. The power supply has to be adjusted down to less than ±10 V before a worsening of the THD could be measured. And finally, the temperature test: with a hair dryer on a hot setting the entire breadboard was 'tortured'. While the actual temperature of each of the individual components is undefined when using this method it is nevertheless a good and quick test to get a feel for the sensitivity of the circuit to temperature changes. The result: The distortion remains low and the amplitude reduces by about 0.3 dB.
The measured distortion of the oscillator is in the vicinity of -106 dB (0.0005%). I had to shield the breadboard with an earthed metal plate underneath to suppress hum.
There is another simple way to obtain lower distortion: for R7 take a 1.5 kΩ resistor and fit a capacitor of 100 nF between the output and ground. In my setup, and with some effort, I was able to measure a distortion of −108 dB (0.0004%).
Certainly, if you have access to the appropriate test equipment, this circuit lends itself very well to further experimentation. Even I was ultimately obstructed by operat-

ing at the limits of the distortion measurement equipment, so there is the possibility I haven't yet been able to obtain the best performance that can be achieved.

Other lamps

During these experiments various other lamps were tried as well. In principle, any lamp with a voltage of up to 10 V and a current of less than 40 mA could be used. As a guide, you can assume that if the voltage across the lamp in the circuit has to be 1/10 of the nominal lamp voltage (U_L); the current through the lamp then has a value of about a quarter of the nominal lamp operating current (I_L).

If we start with an output voltage of 3 V, then we can calculate the values of R5 and R6 as follows:

$$R5 = \frac{\left(3V - \frac{1}{10}U_L\right)}{\frac{1}{4}I_L}$$

and

$$R6 = \left(\frac{30V}{U_L} - 1\right) \cdot 5k\Omega$$

Where U_L = Nominal lamp voltage, I_L = Nominal lamp current

The calculated values are a guide. In practice you will obtain a properly function oscillator when using these values, at least with the various types of lamps I tried. For the best results you will have to experiment a little with these values, because the U-I characteristic of a particular lamp is not exactly fixed. In this way you can play with the output voltage, distortion and switch on time (the amount of time it takes between the switching-on of the power supply voltage and obtaining an output signal with minimal distortion and stable amplitude).

Of the various lamps that were tried, at least the following two types are quite readily available:

- Wire terminal lamp 10 V/14 mA, type nr. 1869. Available from, among others, Mouser (606-CM1869), Digi-Key (289-1227-ND). Reasonable results were obtained with R5 = 330 Ω and R6 = 10 kΩ. With this lamp the switch-on time is a little on the high side (more than 5 seconds).
- Wire terminal lamp 5 V/21 mA type nr. 6022: Mouser (606-6022), Farnell (2078333). Good results were obtained with R5 = 470 Ω and R6 = 33 kΩ.

A final remark about the choice of lamp: Using a bicycle rear light lamp (6 V/50 mA) is not recommended. I measured two of these lamps and both of them had a current consumption at 6 V that was greater than 70 mA!

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Web links and literature

[1] Bridge Circuits, Application Note 43, Linear Technology Corp.: http://cds.linear.com/docs/en/application-note/an43f.pdf

[2] 1000-Hz Sine Wave Generator, Elektor December 1994

[3] http://sound.westhost.com/articles/sinewave.htm

[4] www.moorepage.net/RC.html

[5] www.jensign.com/RMAA/Wien_RMAA/