WORKING WITH OP-AMPS

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Part 3

Op-amps used in a switching mode are essentially generators of square-waves. Control of repetition frequency, pulse length, mark/space ratio and delay time are possible. What precisely is controlled depends upon the exact nature of the circuit. Thus, astable circuits generate continuous square-waves, variable in frequency and mark/space ratio; monostable circuits produce pulses of defined length or time delays, while bistables may be thought of as temporary stores of binary data. Thus it is that the op-amp, usually considered as a linear device, crosses right over into the digital field.

These basic 'building blocks' were covered in Part Two of this series. In Part One, one of the circuits discussed was the 'integrator' which, it may be remembered, produced a linear ramp as a result of a step of voltage at its input. Therefore, if the latter circuit were fed with a train of square-waves, its response would be to generate a continuous triangular waveform. The point is that the ability to convert from one type of waveform to another gives rise to the idea of a circuit that is capable of producing several quite different but 'frequency related' waveforms simultaneously — in other words, a 'function generator'. This 'first stage development' is shown in Figure 1 in the form of the 'hysteresis oscillator'. Two outputs, square-wave and triangle, are produced by the technique mentioned above.

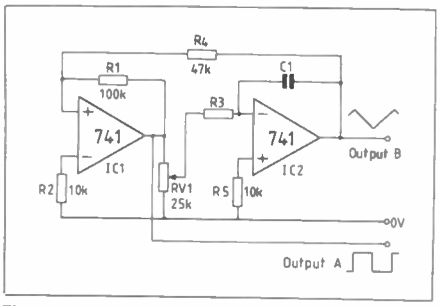

Figure 1. The hysteresis oscillator.

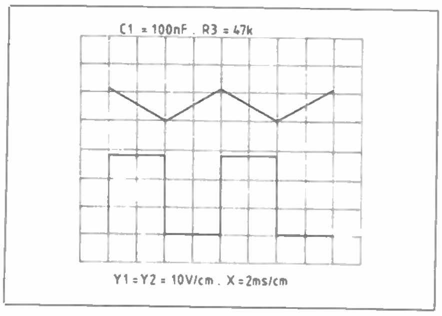

Figure 2. Waveforms of the hysteresis oscillator.

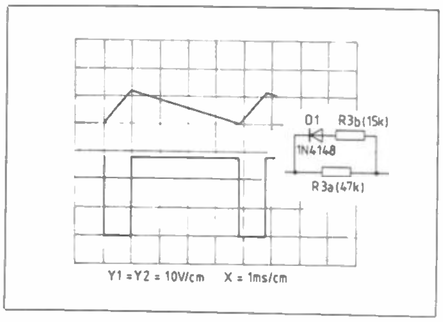

Figure 3. Waveforms of an asymmetric circuit.

The Hysteresis Oscillator

To understand how the circuit works, assume that the output of IC1 is initially in positive saturation i.e. at some voltage +V volts. Then, a current given by V/R3 will flow to charge the feedback capacitor C1 of the integrator IC2. As a result, the output of IC2 will fall linearly and continue to do so until it reaches -V/2 volts; this is output B, the triangle waveform. At this instant, the output of IC1 is forced to switch from positive saturation to negative saturation because of the fed back voltage at the junction of R1 and R4. What then follows is similar to what has been described except that the output of IC2 now 'rises' linearly until it reaches the next 'switch-on' point at +V/2 volts, from which the whole cycle repeats again, and so on indefinitely.

Thus, output B 'runs' alternately between the amplitude limits of +V/2 and -V/2 volts while, simultaneously, output A switches between the amplitude limits of +V and -V volts. The periodic time of either excursion is R3.C1 seconds so that the repetition frequency of the output is equal to 1/(2.R3.C1) Hz — R3 in ohms and C1 in Farads.

To take an example, if a frequency of 100Hz is required and a 100nF capacitor is available, the required value of resistor is found by substituting these values into the formula which, after transposing and evaluating, gives R3 as 50k. An obvious way of adjusting the frequency to exactly 100Hz is to use, for R3, a fixed 47k resistor in series with a 5k pre-set potentiometer. This formula for the frequency is based upon the circuit values given in Figure 1. Changing the ratio R4/R1 moves the switch-on point in time, which then controls the amplitude of output B and obviously changes the frequency of operation. The limiting factor is that the ratio of R4/R1 must be unity or less, otherwise the circuit will stop oscillating. The frequency also depends upon the amplitude of the square-wave fed to IC2 because, as was explained in Part Two, the slope of the wave out of an integrator depends not only on the integrator time constant, but also on the magnitude of the step input. So, by feeding IC2, not from the full output of IC1 but from a portion of it (up to the maximum) derived from a potentiometer, continuously variable control of frequency is available over a reasonably wide range. Using the values given in Figure 1, the variation of frequency available using RV1 was from about 6.25Hz to 125Hz. The waveforms obtained at both outputs at 125Hz are shown in Figure 2.

Sometimes a mark/space ratio other than unity is required; to do this it is necessary to introduce some asymmetry into the circuit. To achieve this objective means finding a frequency-dependent component and making it change its value automatically on alternate half-cycles. This implies the use of a diode to provide two unequal 'polarity-conscious' paths. The obvious choice of component is R3 and the modification is shown in Figure 3 together with sample waveforms obtained. On the half-cycles when the output from IC1 is positive-going, D1 is non-conducting and R3 equals R3a i.e. equals 47k. But, on the negative half-cycles, D1 conducts and puts R3a and R3b in parallel — an effective value of R3 of 11.4k. The mark/space ratio should then be 47/11.4, that is slightly over 4:1. This is verified by the waveforms of Figure 3, which shows that the actual mark/space ratio obtained was 3.8:1, within the tolerance of the resistors used (10%).

Sine-shaping Circuit

The hysteresis oscillator, which produces two different but related waveforms, has been referred to as the 'first stage development' of a function generator. This is justifiable if it is accepted that such a circuit cannot really be said to be complete unless there is also a sine-wave output. There are various ways of adding this facility but one of interest is the method of using an op-amp inverting amplifier with a sine-wave approximation network to develop the sinewave output from a triangle input. A number of diodes are used in the feedback path of the op-amp that conduct at different levels of the input, changing the gain and hence the slope of the output. The sinewave is thus represented by a succession of different slopes and quite a reasonable approximation is possible. The arrangement of the diodes and associated resistors is shown in Figure 4, together with a sketch of the principle involved.

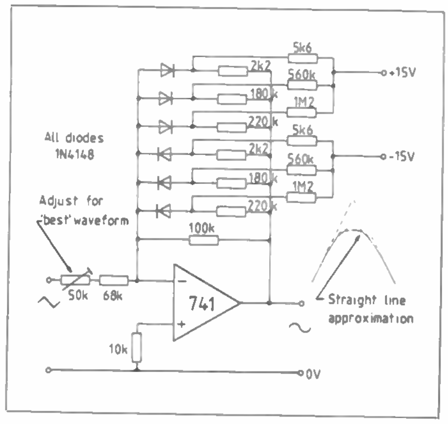

Figure 4. Sine-shaping circuit.

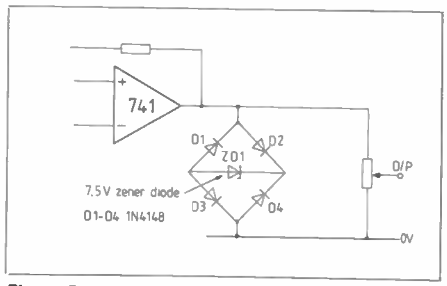

Figure 5. Zener diode amplitude limiter.

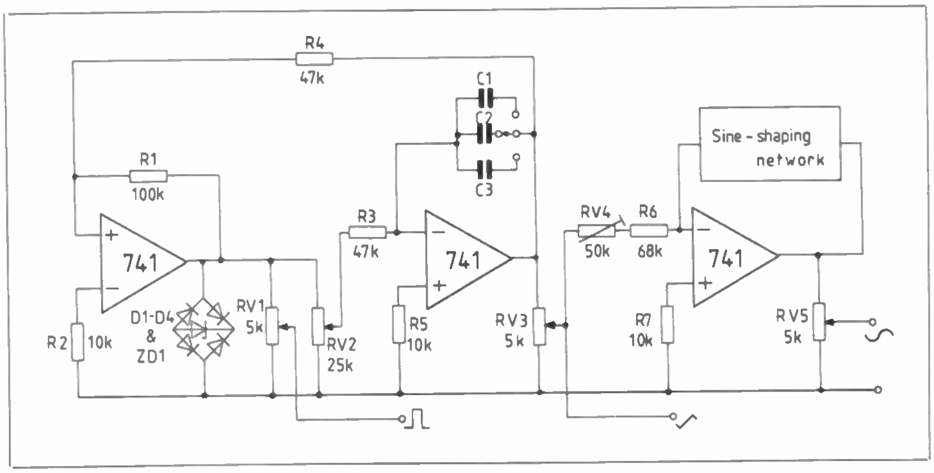

Figure 6. Function generator.

Square-wave Clamping

The waveform of the square-wave generated by the circuit of Figure 1 is good at the low frequencies but, in the kHz region begins to show some 'sag'. An obvious way of getting over this is to clip off the peaks of the square-wave or, to describe the process more correctly, to clamp the square-wave to a predetermined level, well below that at which the sag is likely to occur. A zener diode will make an effective and consistent clamp and if just one diode is used, together with a diode bridge, as shown in Figure 5, the clamping action will be precisely symmetrical, the zener diode acting equally on both half-cycles of the square-waveform.

A Function Generator

To make a function generator that is at all versatile, range-switching of frequency and control of amplitudes is desirable. The latter can most easily be provided by potentiometers at each output, and the former requirement can be met by switching the value of C1; fine control of frequency will be by use of the potentiometer between stages. A scheme incorporating all of the ideas discussed so far is shown in Figure 6. Most component values are shown but the values of C1, C2 and C3 are left to the experimenter to select for himself, sufficient information having now been given for him to be able to do this.

An Alternative Approach

The method of generating three related functions just described was based upon the use of a square/triangle generator with the sinewave function being added on. But the versatility of the op-amp is such as to allow us to 'swap' the process around and start off with the sinewave. From this point, the sinewave can be 'squared off' (giving the square-wave output) and this waveform, in turn, integrated in an op-amp integrator to give the triangle output. What is then needed, as a starting point, is a sinewave oscillator of the RC type.

The Twin-Tee Oscillator

The frequency-selective network that starts and maintains the oscillations in this circuit is a 'twin-tee' filter network. In Figure 7, the component values are based upon a resistance R and a capacitance C. The shunt resistance branch, nominally equal in value to R/2, is actually de-tuned slightly by a 2k5 pre-set. The phase-shift through the network is then 180° with some attenuation (dependent upon the degree of de-tuning). The op-amp has 180° of phase-shift as well between the inverting input and the output and very high gain. As a result, the 'loop phase shift' is

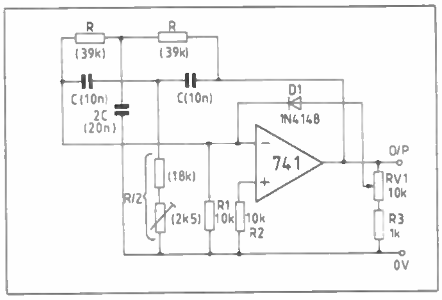

Figure 7. Twin-tee oscillator.

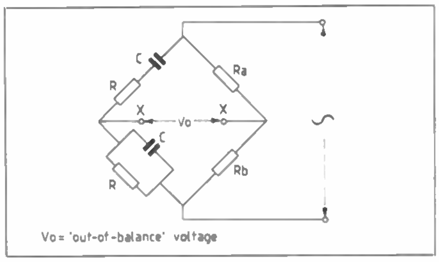

Figure 8. The Wien bridge.

360°, giving positive feedback and with the R/2 arm adjusted carefully, the circuit bursts into oscillation; the 2k5 pre-set should be carefully adjusted to give a sine-wave with minimum distortion. All of this happens at a unique frequency which equals $1/(2\pi.R.C)$.

Even so, the degree of distortion may not be acceptable so a stabiliser can then be used that will give some improvement. A simple stabiliser, shown in Figure 7, consists of D1, R3 and RV1, the latter acting as an output control. The improvement in waveform with this simple modification is worthwhile, though there is some reduction in the maximum output. With 15V supplies, the unstabilised circuit can give 27V peak to peak output, which is reduced to about 8.5V peak to peak when the stabiliser is fitted, still a worthwhile output.

With the values of R, C, R/2 and 2C shown in brackets in Figure 7, the design frequency was 400Hz. Using 5% resistors and 10% capacitors, the measured frequency on test was 435Hz, which is within the allowable limits. Obviously the use of closer tolerance components would have given a result closer to the design figure.

To change the frequency of the twin-tee oscillator means changing the values of at least three components simultaneously (e.g. all three resistors in the filter network). This is not usually very practicable so this circuit is unlikely to be chosen except as a fixed frequency oscillator.

The Wien Bridge Oscillator

This might justifiably be called the 'classic RC oscillator', since it is almost universally used to generate low-frequency sinewaves, especially where a wide frequency range is required. It is based on the properties of the Wien network, which is an RC combination that has zero phase-shift and a loss of 3:1 at a frequency equal to $1/(2\pi R.C.)$. This formula assumes that both resistors have the same value and also both capacitors are equal, which is usually the case. At first sight it might appear that all that is needed is an amplifier with a gain of 3 and zero phase-shift. However, it is better in practice to use a high-gain amplifier and include negative feedback to improve the stability of the circuit. This implies some sort of balance between the two types of feedback, positive and negative. This is achieved by adding two extra resistors to form a bridge, this being shown in Figure 8. It is these two resistors that provide the negative feedback, since they form a potential divider across the output and are connected at their junction to the inverting input of an op-amp in the final circuit. When this bridge is just 'off balance', a small voltage at the oscillatory frequency appears across X-X. It is this small voltage that is subject to the high gain of the op-amp to develop the output voltage.

A possible circuit is shown in Figure 9. One point that is to be noticed immediately is that the frequency is controlled by twin-gang potentiometers RV1/RV2 so that a resistance change from R1 to (R1 + RV1) is possible in the series arm, with an identical change taking place simultaneously in the parallel arm. Another feature of the circuit is that Ra consists of a potentiometer RV3 and two diodes, D1 and D2, back to back. The idea is to provide a non-linear element that will control the degree of out-of-balance of the bridge automatically to compensate for amplitude variations. RV3 is adjusted for the best waveform.

With the values shown in Figure 9 the frequency range obtained was from 220Hz to 1kHz, and the output level was about 1.25V peak to peak. Further ranges can be added by switching the capacitor values.

A more effective stabiliser uses a NTC thermistor, such as an R53, in place of the potentiometer/diodes network. However, these thermistors are extremely expensive and rarely justified except in a permanent design of some sophistication.

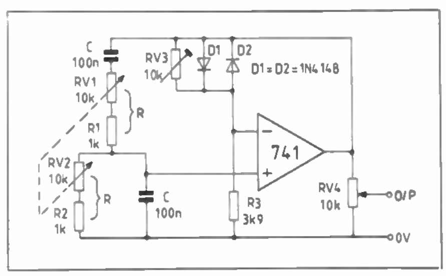

Figure 9. The Wien bridge oscillator.

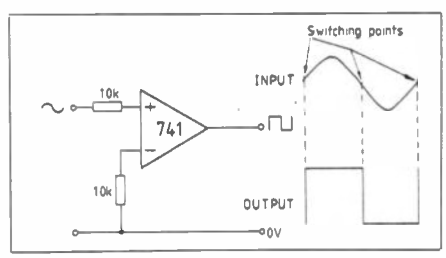

Figure 10. Sine-square converter.

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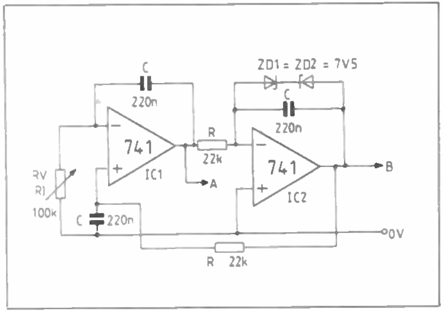

Figure 11. The quadrature oscillator.

The Sine-Square Converter

Having produced the required sinewave, the next step is to square it off. A very simple way of doing this is to use the op-amp comparator, shown in Figure 10. The inverting input is tied to 0V and the sinewave input is applied to the non-inverting input. Every time the input goes positive, even by a fraction of a milli-volt, the output goes into positive saturation, and for negative half-cycles at the input, the output goes into negative saturation. So the sinewave is very efficiently converted into a square-wave, which can then be integrated, using a standard op-amp integrator, to develop the triangular waveform.

The Quadrature Oscillator

Having dealt now with several circuits that produce different time-related waveforms, it is interesting to consider a circuit in which the waveforms are identical but differ by a fixed phase angle, whatever the frequency. The actual phase angle is 90° so that the sinewaves are in 'quadrature', hence the name of the circuit, which appears in Figure 11. Two integrators are used, IC1 and IC2, the former being a non-inverting type and the latter an inverting type. The frequency of the output waveforms is determined by the time constants obtained from three resistors and three capacitors, known as R and C respectively on the basis that they are nominally equal. In practice, one of the resistors is a potentiometer RV, which is carefully adjusted until the given outputs A and B are obtained, best viewed on a double-beam CRO. If RV is turned too far one way, the circuit stops oscillating, and if too far the other way, the waveforms become a triangle and a square-wave! However, the correct setting of RV is easily found and the sinewaves are then quite stable and of excellent waveform. An amplitude limiter is included in the form of two zener diodes connected back to back.

The formula for the frequency of operation is that $f=1/(2\pi R.C)$ and, with the values given in Figure 11, the circuit oscillated at 33Hz. It will work quite happily over a wide range of frequencies. For example, with R=47k; C=220n, the frequency is as low as 14Hz and with R=1k; C=47n, the frequency is then 3.7kHz. At the higher frequencies a smaller value of RV makes the setting less critical.