WORKING WITH OP~AMPS

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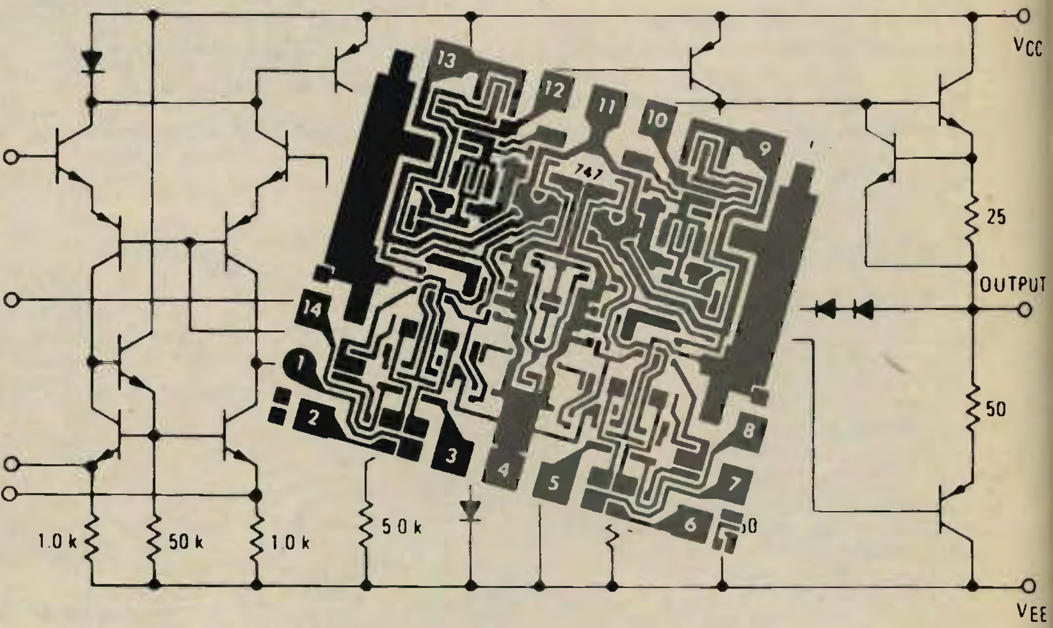
Part 2



The first part of this series introduced the op-amp and gave an insight into its versatile nature. Now its specific role as a waveform generator will be illustrated. The most useful waveforms are undoubtedly the sine-wave, square-wave, triangle and sawtooth, all of which can be produced by this device. As a result, it will be appreciated that what is being demonstrated is not only its linear use for generating sine-waves but also its switching mode when giving a square-wave output.

The Astable Multivibrator

This circuit (Figure 1) looks unfamiliar when compared with the discrete component equivalent. One obvious difference is that there is only one RC 'timing' circuit (R1, C1). This saves components but means that the mark to space ratio of the square-wave output will always be 1:1. Adjusting either R1 or C1 only changes the frequency. The resistors R2 and R3 form a potential divider between the output and the 0V line so that, whatever level exists at the output (+Vs or -Vs), the non-inverting (+) input is always at a fixed proportion of it.

The clue to the mode of operation lies in this last statement. The non-inverting input is held at a fixed reference voltage, either positive or negative, while at the instant that power is applied to the circuit, the inverting input is at 0V since C1 is uncharged. As a result, the output goes to either +Vs or -Vs (it does not matter which, say +Vs), in which case the non-inverting input will be at a potential equal to +Vs [R3/(R2 + R3)]. Since there is zero phase-shift between this input and the output, the latter level is effectively 'latched' to +Vs. The circuit is now resting in one of its two 'quasi-stable' states and will do so until something upsets the equilibrium. This 'something' will occur when the exponentially rising voltage at the junction of R1 and C1 reaches the potential of the non-inverting input. Then, as this exponential voltage just becomes slightly more positive than the latter potential, the circuit will start to change state. The op-amp's very high gain ensures that the output switches rapidly from +Vs to -Vs and the potential at the non-inverting input will now reverse its polarity, latching the circuit into the new state.

The current flowing in R1 also changes direction so that the potential of the inverting input begins to fall exponentially from +Vs [R3/(R2 + R3)] towards -Vs. However, when it reaches -Vs [R3/(R2 + R3)], the circuit switches back into its original state and the cycle repeats indefinitely.

The time for which the circuit remains in one state is governed by the time constant of R1 and C1 and the voltage at the junction of R2 and R3. Frequency can, therefore, be controlled in a number of ways: by using a potentiometer for R1 and/or switching the value of C1 to give several ranges, or using a resistor chain with a potentiometer instead of R2 and R3, so varying the point in time at which the circuit changes states.

With the exponential law of growth as a basis, it is a fairly easy matter to derive an expression for frequency in terms of R1, R2, R3 and C1, thus stating precisely how frequency depends upon these circuit constants.

The time between instants of switching is found to be given by:

$t_s = C1.R1.\log_e [1 + (2R3/R2)]$

and $f = 1/(2t_s)$

C1(nF)	Frequency (Hz)		Error
	Measured	Calculated	
10	1190	1371	-13%
47	290	292	-0.7%
100	143	137	+4.4%
220	65	62.3	+4.3%
470	30.8	29.2	+5.5%
1000(1u)	14.3	13.7	+4.4%

Table 1. Frequency vs. timing capacitor value for the circuit shown in Figure 1.

Having derived this expression for frequency, the next step was to verify it. Close tolerance resistors (5%) were used for R1, R2 and R3 and values of C1 were set on a decade capacitor box, so as to give the results some credibility. The values chosen for the resistors were R1 = R2 = 100k and R3 was 22k. The results obtained are shown in Table 1, which also includes the calculated values of frequency and the percentage errors. Except at the highest frequency, the errors are within acceptable limits. Therefore, for generators up to a few hundred Hertz, the formula can be used with confidence.

A limitation of the 741 is its inability to switch rapidly between opposite states. This limit is expressed in op-amps by the 'slewing rate', which is given in V/us. Figure 2 shows that slewing rate is simply the slope of voltage/time as the output tries to swing from one saturation level to the other. For the 741 the maximum slewing rate is usually quoted as 0.5V/us so that, with a ±15V supply, a complete transition from, say, -15V to +15V cannot be achieved in less than 30 x 0.5 = 15us, in the best case. Since switching circuits are being discussed, it is as well to be aware of possible limitations. For example, the astable circuit of Figure 1 while producing an acceptably square waveform at 1kHz, showed a marked slope on the leading and trailing edges at 5kHz.

Figure 3 shows a slightly modified form of

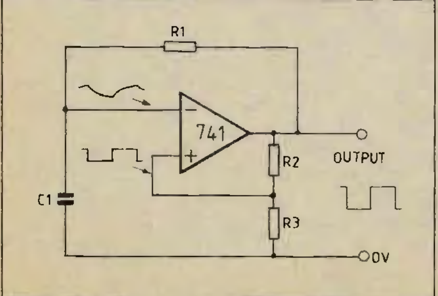


Figure 1. Op-amp astable circuit.

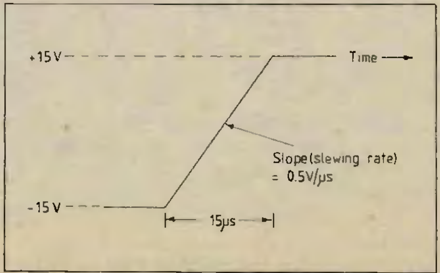


Figure 2. Illustrating 'stewing-rate'.

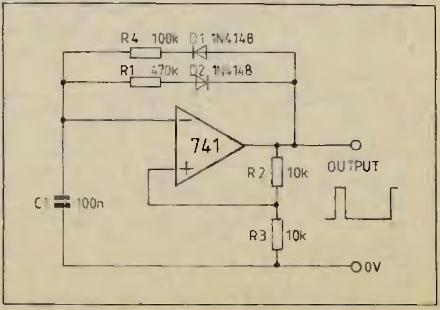


Figure 3. Non-symmetrical astable circuit.

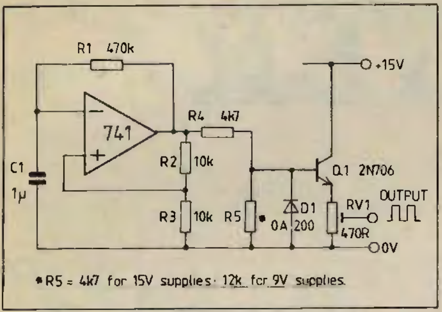


Figure 4. A 1Hz TTL generator.

the astable circuit, in which the restriction of a unity mark to space ratio has been lifted. This is achieved by placing diodes D1 and D2 in the feedback paths so that the polarity of the output voltage selects which of the feedback resistors is in circuit on a particular half-cycle. This gives two time constants which are quite independent of each other — R4, C1 on positive half-cycles and R1, C1 on negative half-cycles. With the values shown this gives a short mark and a long space of 11ms and 52ms respectively.

A 1Hz TTL Generator

For digital experiments a low frequency square-wave generator is very useful, for example, for testing counters and shift registers. An output at about 1Hz is slow enough to allow events to be observed with ease and, using the op-amp astable circuit, a frequency of this value is easily achieved without the need for excessively large capacitor values.

The design is straightforward. As a starting point, let R2 = R3 = 10k (quite an arbitrary choice, which could be adjusted later if necessary). The only other components to be decided now are the timing components and it is convenient to choose a value of capacitance first, then work out the corresponding resistor value; this allows greater freedom of choice in component values. The largest value of non-electrolytic capacitor is about 1uF, so this value is used with the previously derived formula to obtain the resistor value. The formula then looks like this:

$t_s = 0.5 = 10^6 \times R1 \times \log_e$ (at 1Hz $t_s = 0.5$ secs.)
from which R1 = 455K

The nearest preferred value is 470k, which actually gives a frequency of 0.97Hz (neglecting component tolerances), which should certainly be close enough for most purposes. In fact, when the circuit was wired up, using 5% resistors and a 10% polyester capacitor, the error from the design value of 1Hz was too small to measure.

The next step, after getting the circuit to perform at the right frequency, is to make it TTL compatible, which means converting a ±14V swing about 0V (the output does not quite reach 15V) into a wholly positive 5V square-wave. A few additional components lead to the final circuit of Figure 4, which shows the attenuation of the op-amp output (R4 and R5) to a total swing of about 6V, this then being 'clamped' to 0V by the action of Q1, which also 'buffers' the output to provide enough drive for a number of TTL circuits. Diode D1 also has a clamping action, but its true purpose is to protect the base-emitter diode of Q1 against excessive negative V_{BE} on negative going output swings of the op-amp. The emitter resistor of Q1 is a potentiometer (preset) so that the amplitude of the output can be adjusted to precisely 5V.

Obviously the generator could be made to produce a range of frequencies by switching different values of R1 or C1.

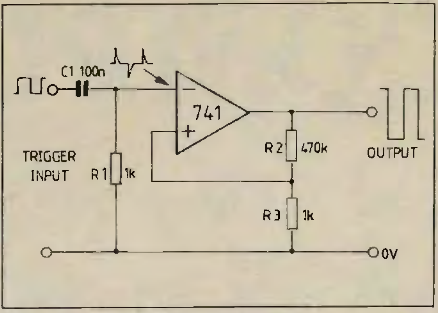


Figure 5. Op-amp bistable circuit.

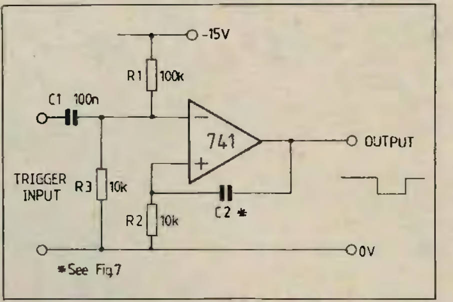


Figure 6. Op-amp monostable circuit.

The Bistable Multivibrator

Bistable action may not normally be associated with the op-amp, i.e. a circuit which is capable of resting indefinitely in one of two stable states. But, as was seen with the astable circuit, feedback from the output to the non-inverting input, will latch the circuit into a state of either positive or negative saturation. If, meanwhile, the inverting input is held at 0V, the circuit stays in this state until a trigger of some sort causes a change of state. This trigger is applied to the inverting input and the only stipulation is that its peak value must exceed the voltage at the non-inverting input; the circuit will even trigger on sine-wave inputs.

Figure 5 shows such a circuit. The inverting input is held at 0V by resistor R1 while the non-inverting input is taken back to the junction of the divider R2 and R3 across the output. Thus, depending upon the current state of the circuit, the bistable is latched into this state by a voltage at the non-inverting input equal to ±R3/(R2 + R3) x output voltage. For the values given and a ±15V supply, this voltage is (1/471) x 14, which is approximately 30mV, more than enough to take the circuit into saturation.

The trigger input is capacitively coupled to the inverting input by C1 which, with R1 differentiates the input if it is a pulse or square waveform. This action produces a series of alternate positive and negative trigger pulses which, coinciding as they do with the leading and trailing edges of the original square-wave input, mean that the output is at the same frequency as the input but reversed in phase and of larger amplitude. There is no 'divide-by-two' action and the circuit acts effectively as a 'pulse amplifier'.

This bistable circuit is not particularly fast; frequencies up to about 300Hz give a good square-wave output but, thereafter, the risetime suffers markedly.

Returning to the absence of an inherent divide-by-two action, this limitation can be removed if R2 is replaced by a parallel RC combination consisting of a 1M resistor and a 100nF capacitor, and R3 is replaced by a 470k resistor. The 100nF capacitor introduces a time constant whose purpose is to ensure that, when the circuit is initially switched, say, by the leading edge of a square pulse, it does not change state again on the trailing edge of that pulse but 'waits' for the leading edge of the next pulse. The value of 100nF is large enough for pulses up to 50ms in length but needs to be increased for longer pulses.

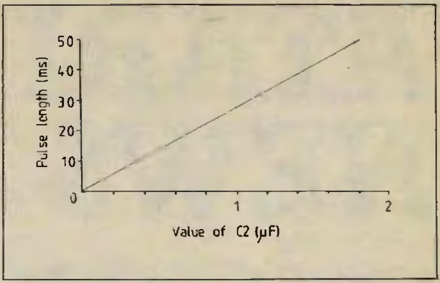


Figure 7. Pulse length graph for monostable circuit shown in Figure 6.

The Monostable Multivibrator

This, the last of the 'trio' of multivibrator circuits, has one stable state (in which it rests until triggered) and one 'quasi-stable' state (in which, after triggering, it remains for a pre-determined time, decreed by circuit constants). Although monostables can be realised with discrete components or obtained in TTL integrated circuits, it may now be appreciated that this circuit can also be produced with the ubiquitous op-amp. In this form it appears in Figure 6.

For a monostable to exist in a stable state, there must be a bias holding the circuit in that state. This bias is provided by taking the inverting input to -15V through resistor R1. The output of the op-amp is, therefore, normally in positive saturation. It is then triggered into the quasi-stable state by a square-wave or pulse input. This is differentiated by C1 and R3, only the positive pulses produced having any effect on the circuit. As a result, the circuit switches over to negative saturation where it is held by the large negative potential instantly coupled back to the non-inverting input by C2. Of course, this state cannot be sustained for long because, at this initial instant, the full negative supply voltage exists across R2 so that a charging current flows through R2 and the potential of the non-inverting input rises exponentially towards 0V. When it reaches the same value of negative voltage as at the inverting input (about -1.4V), the circuit switches back to positive saturation.

The time constant for the recovery is CR, R2 and it is possible to derive a formula for the length of the positive pulse produced at the output as a result of this action. However, in this circuit, unlike the astable, there is a linear relationship between pulse length and capacitance value so that a useful graph can be plotted between these two quantities (Figure 7). This covers a range of pulse lengths from 0 to 50ms, corresponding to values of C2 in the range 0 to 2uF. Obviously the range can be extended further by using higher values of C2 or a higher value of R2.

This type of circuit functions as a 'pulse-stretcher'; a short pulse is used to generate a much longer pulse. Or it can be used as a regenerator of pulses since the input waveform is not too critical provided that it can cause the required change of state, but the output pulse will always be of good square form.

As waveform generators, these multivibrators all generate square-waves in one way or another; each has its own use. Op-amps can also be used to generate 'derived' waveforms, such as the triangle and sawtooth; they can also be used in sine-wave oscillators. Generators of these types will be the subject of the next article. ■