Configurations

Transistors as amplifiers, transistors as multivibrators — now we consider transistors as sawtooth generators.

By Ian Sinclair

THE TIMEBASE is a circuit which generates a sawtooth waveform, on whose voltage changes linearly with time: a graph of voltage plotted against time will be shown in Fig. 1 (though it may be either positive-going or negative-going). The best known application is in oscilloscope timebases, but the circuit can also find use in digital-analogue converters and in timing circuits.

The most simple timing circuit is, of course, a capacitor charging through a resistor (Fig. 2). The time constant CR determines the total charging time which, though theoretically infinite, is in practice about four or five times the length of the time constant. The graph shape of voltage plotted against time is, however, exponential rather than linear because the charging current drops as the capacitor charges. All timebases of the capacitor-charging type therefore need some method of keeping the charging current constant as the voltage across the capacitor rises.

Transistor Control

In the days of tubes, many elaborate circuits were devised to overcome the problem of constant current control, but it took the development of the transistor to come up with a really simple system with good performance. A transistor whose base-emitter junction passes a constant current will also pass a (larger) constant current between its collector and its emitter, and this current can be maintained up to the level where the collector voltage is less than half a volt different from the emitter voltage.

Figure 3 shows a simple timebase circuit using this principle. Q1 is a switching transistor which is normally conducting,

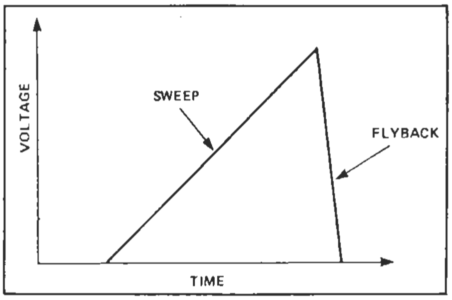

Fig. 1 The waveform of a perfect timebase — this should be a straight line.

keeping the voltage across the capacitor low. Q2 is a PNP transistor whose base current is set by the resistor chain R2, R3, RV1, and which can be varied by altering the value of RV1. Since the base current is constant, the collector current will also be constant. Q3 is simply an emitter-follower to avoid non-linear effects which would be caused by a resistive load connected

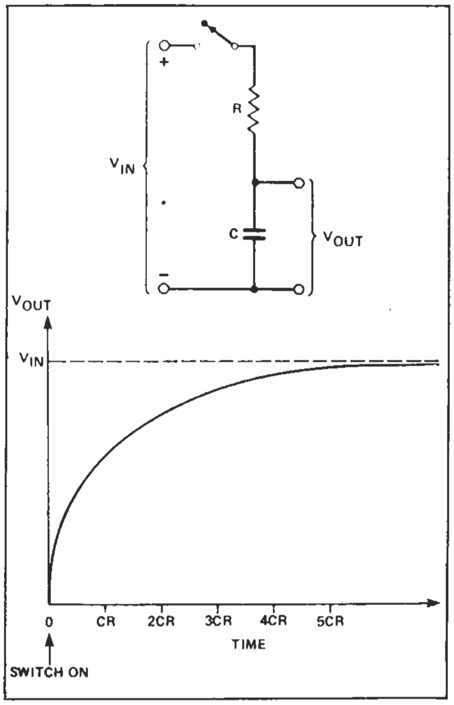

Fig. 2 Capacitor charging. When a capacitor is charged through a resistor the waveform is an exponential rather than a straight line.

across the charging capacitor (since a resistance takes more current as the voltage across it is increased). For the best results, Q3 should be a transistor with a high h_{fe} value, and a double emitter-follower is often preferable to ensure the highest possible input resistance.

The action is as follows. When Q1 is cut off by a negative pulse at its base, capacitor C1 can be charged by current flowing through Q2. This current will not change until the collector voltage of Q2 has reached a value close to the positive supply voltage, so that the wave form is linear up to this region. If Q1 remains cut off, the waveform will then flatten off, but if Q1 is switched on again before this point is reached, then a good sawtooth shape is preserved.

Timing The Timebase

The action depends to a large extent on switching the transistor Q1 at the correct times, and all timebases consist basically of two sections — a square wave generator which handles the switching and a sawtooth generator which provides the

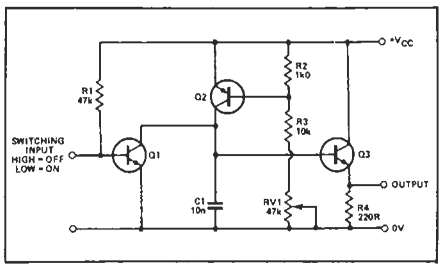

Fig. 3 Using a transistor in place of a resistor for capacitor charging. Since the current through the transistor remains constant, the sweep waveform is straight rather than exponential.

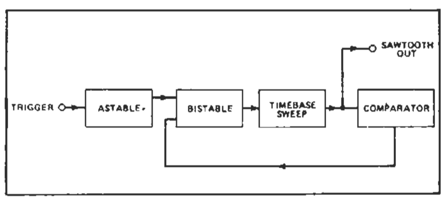

Fig. 4 Block diagram of an oscilloscope timebase.

desired waveform. An oscilloscope timebase would use a level-detecting circuit at the output to ensure that the switching transistor Q1 was switched off before the voltage level at the output reached the non-linear region — a block diagram with waveforms is shown in Fig. 4. In this arrangement, the repetition rate of the timebase is determined by an astable which provides a trigger pulse. The trigger pulse sets the bistable, which in turn cuts off the switching transistor of the timebase generator and so starts the charging of the capacitor. When the charging has reached some preset voltage level, the level detector (comparator) circuit switches the bistable back, discharging the capacitor ready for another sweep. For many oscilloscope purposes, the astable is set to run freely at a low speed, and is synchronised to whatever waveform is to be displayed — this is the auto timebase system found on most modern oscilloscopes. The sweep speed is then determined by the time constant of the charging capacitor.

The use of a transistor as a constant current device for a timebase is good enough for many purposes, but two other methods of creating linear sweep waveforms from the basic capacitor charging circuit have been well established

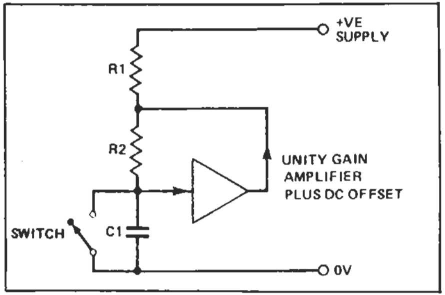

Fig. 5 The principle of the bootstrap timebase circuit.

for many decades in oscilloscope circuitry. One of these is the bootstrap circuit. Bootstraping is positive feedback applied over a circuit in which the gain is less than unity, so that it does not cause oscillation.

Bootstraps

The principle of the bootstrap is shown in Fig. 5. A capacitor is charged through two series resistors, and a unity-gain amplifier is connected so that the voltage across the capacitor can be applied, in phase but with its DC level shifted, to the point where the resistors join. When the capacitor starts to charge, the increase of voltage across the capacitor causes a matching increase of voltage across R2, so that the voltage across R2 has not changed in this time. Since the voltage across R2 is constant, the current through R2 is also constant, which is the condition for a linear sweep.

The bootstrap depends on being able to keep the voltage at the junction of the resistors at a constant amount greater than the voltage across the capacitor. The whole idea seemed so absurd when it was first proposed that the (US) inventor remarked that it seemed "rather like lifting yourself by your own bootstraps". As so often happens, the name stuck.

A practical form of the timebase is shown in Fig. 6. Q1 is, as before, the switching transistor which starts and stops the sweep. The charging resistor chain consists of R2, R3 and RV1, of which R3 is a limiting resistor whose value is set so that excessive current does not flow through Q1 when the variable is set at its minimum value. D1 is used to prevent C1 from discharging below about 0V7, ensuring that Q2 will not switch off, causing non-linearity. If Q2 is allowed to switch off, then the timebase output will have a decided 'kink' at the voltage at which Q2 switches on.

Q2 is an emitter-follower, whose emitter is connected through a zener diode ZD1 to the junction of R2 and R3. The zener diode, along with the base-emitter voltage drop of Q2 determines the voltage across R3 and RV1, so that the charging rate can be calculated. For example, suppose the voltage is 6V, the values of RV1 and R3 add up to 56k and C1 is 22nF. The charging current I is 6/56 mA, which is 0.107 mA, and the rate of change of voltage across C1 is I/C1. Using units of milliamps and nanofarads, the rate of rise of voltage will be in volts/microsecond, and the example gives 0.00486, equivalent to 4.86 volts per millisecond. If you know the sensitivity figure for the cathode ray tube for which the timebase is to be used (in terms of centimetres of deflection per volt), then you can calculate what amount of amplification will be needed to obtain full screen coverage, and what time constants will be needed for the various scan speeds.

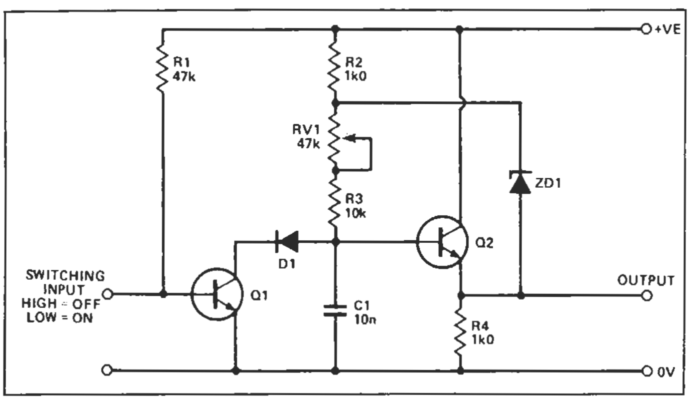

Fig. 6 A practical form of the bootstrap circuit, using an emitter-follower as the unity-gain amplifier.

There are limitations on the voltage gain of the emitter follower and the frequency range over which the zener diode remains effective, but with suitable choice of components, good timebase circuits can be designed around this core configuration. Commercial circuits of this type often look remarkably complicated, but once the bootstrap section is separated from the other parts of the complete timebase (the triggering and the comparator section), the essential simplicity of the circuit can be seen.

The Miller Alternative

The other basic capacitor charging circuit is the Miller integrator. These two circuits, the bootstrap and the Miller, were curiously polarised for many years, with the bootstrap used on US equipment and the Miller on UK equipment almost exclusively, but this is no longer completely true.

The Miller timebase is named after (you guessed it!) Miller, who discovered the result of negative feedback across the anode-grid capacitance of triode tubes. The name became attached to the timebase (which was not designed by Miller) because the Miller timebase makes deliberate use of such feedback to achieve linearity. The basic circuit is shown in Fig. 7, and the most startling thing about it is its simplicity, because the switching transistor is also the current regulator! If we imagine the transistor starting cutoff, then a square wave applied to the input will raise the base voltage until the transistor starts to conduct. When conduction starts, however, the collector voltage will drop, and the negative feedback through C1 will prevent the base voltage from rising to the level of the input voltage. Once this has happened, the base voltage can rise only as fast as the capacitor C1 can be discharged, and the discharge is at a steady rate because of the negative feedback.

The time constant for the Miller integrator is given by the value of R1 and C1 rather than R2 and C1 as you might expect, and the conventional use of the circuit as shown here produces a timebase waveform which is negative-going, with a small 'step', shown in Fig. 8, just at the point where the transistor switches on.

The circuit will operate in the opposite direction, when the 'free' end of R1 is at ground potential. In this case, the voltage at the transistor's collector rises just quickly enough to keep sufficient current flowing into its base (and also R1) to keep it on. In both cases, the simplest way to achieve the fly-back is to connect a diode, D1, in parallel with R1. For operation in the opposite direction from that first described, the direction of the diode must be reversed.

More elaborate versions of the Miller use two stages of amplification with the output in phase, and a low-impedance stage driving the capacitor. Very good results can be obtained, and with a wide-band op-amp used in place of a transistor, excellent timebase linearity is possible.

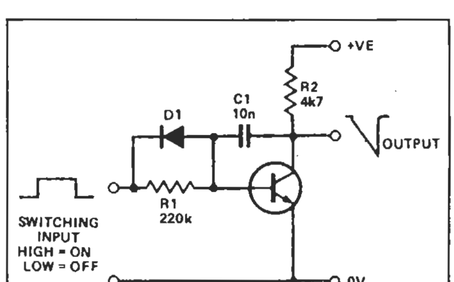

Fig. 7 The basic Miller timebase circuit.

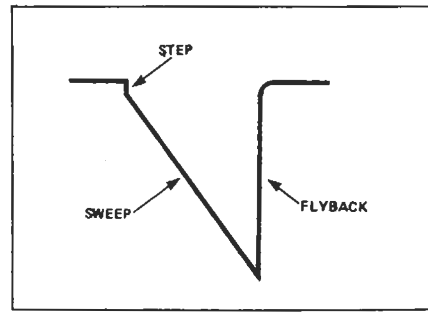

Fig. 8 The waveform from the simple Miller circuit.

Before we leave the subject, timebases can also make use of the growth of current through an inductor. The effect that is used here is the inductive equivalent of capacitor charging, and it is useful because if the inductor is also a deflection coil for a cathode-ray tube, then the timebase and deflection system can be combined. Linearity is much less easy to achieve, however, and one method is the use of a saturable reactor in series with inductor which carries out the timebase action. The inductance of a saturable reactor will vary with the amount of voltage across it in order to keep the current constant. ■