Wireless World Circard

Series 3: Waveform generators

The article on the next two pages shows the waveforms considered in this set of cards; sinewave oscillators and modulated trains of pulses were excluded. It provides an excellent "potted" account of the various methods of waveform generation.

Five cards show triangular-wave generators. As four of them are based on the integrator plus hysteresis switch approach, they also double as rectangular-wave generators. (The fifth uses an emitter-coupled circuit switching a constant current alternately through both directions of a capacitor.)

Card 12, whilst not properly describing a waveform generator, gives some waveshaping circuits for converting triangular waves into approximately sinusoidal ones. One technique described uses an integrator with d.c. negative feedback but the approximation is crude, typically giving 4% harmonic distortion. Better methods (<1% distortion) use non-linear elements in a feedback loop and two circuits are given with diodes and an f.e.t. A fourth waveshaper on this card gives a sawtooth wave from a square and triangle generator.

Examples of the two basic techniques for staircase generation are included—an interesting improved "pump" circuit and the ladder kind of digital-to-analogue converter.

Waveform Generators

As electronics is largely concerned with the generation and processing of electrical signals, the subject of this article could include half of all known circuits. It will be easiest first to exclude certain well-defined classes of generator to be dealt with in later series. For example sine waves are perhaps the most commonly generated waveforms, and the great variety of such circuits warrants separate treatment. Similarly, pulse waveforms have ever-widening applications in communication and digital systems and correspondingly numerous circuits have been published. There remain a number of well-defined waveforms of general usefulness, sufficiently important to qualify for a series to themselves. They include triangle, ramp (linear and exponential), staircase and trapezium waveforms, together with others that are conveniently generated from them. For example, an excellent means of generating a triangular wave requires the repetitive reversal of bias to an integrator by a Schmitt trigger, the output of which is thus a square wave. Where it is possible to modify an existing waveform simply, to provide an approximation to some other desired function, the method is indicated below. It is not possible within the confines of a short article or single set of Circards to do more than outline such methods.

The majority of these generators depend on the charging of a capacitor, though dual circuits using inductors may be devised. To provide a repetitive waveform, the direction of charge flow has to be periodically reversed, and this leads to a major subdivision. The reversal may be such that the charge-rate is comparable for the two directions, in which case the capacitor waveform belongs to the triangular class. If the charge rates differ markedly the waveform approximates to a saw-tooth. In either case the charge rate may be constant or may vary during a half-cycle.

If charge is passed into the capacitor in discrete quantities at regular intervals, then a third type of waveform, the staircase waveform, Fig. 5, is produced. Digital waveform generators using digital-to-analogue (or d/a) converters can also produce stepped waveforms, the staircase being a particular version. If the steps are small enough and sufficient in number then waveforms can be synthesized to any required accuracy and the cost of such generators continues to fall with the increasing range of digital circuits of low cost. To remove the steps from the output is not possible but the use of suitable filters, such as those of series 1 Circards, can reduce the ripple at the step frequency without seriously distorting the synthesized waveform. A particular advantage of the d/a converter method is that no reactive elements are employed as the output frequency is defined exactly by the clock frequency and the division ratio of the counter used.

Ramp and sawtooth generators

In ramp generators a capacitor receives a defined current, constant if the ramp is to be linear. If the current flows for a period determined by some external agency the ramp is said to be triggered, and normally at the end of the ramp period the capacitor is discharged and the source of current removed (or the current by-passed). Such an action is required for the triggered timebase of oscilloscopes. A second mode of operation is where the capacitor discharge is immediately followed by the re-establishment of current flow and the restarting of the cycle is a free-running mode. The parameters of the waveform of interest are linearity of the ramp, accuracy of definition of the end-points and duration of the interval between the end of one forward stroke and the next (flyback). Most applications require a linear ramp, Fig. 2, though the natural tendency is for current and hence rate of charging to fall as the capacitor p.d. increases, Fig. 3. Some circuits have bootstrapping of the voltage drive, so that the p.d. across the current-defining resistor remains constant. Compensation for leakage-current effects to maintain linearity or over-compensation to obtain waveforms as in Fig. 4 are other possibilities if the bootstrap circuit has a gain greater than unity.

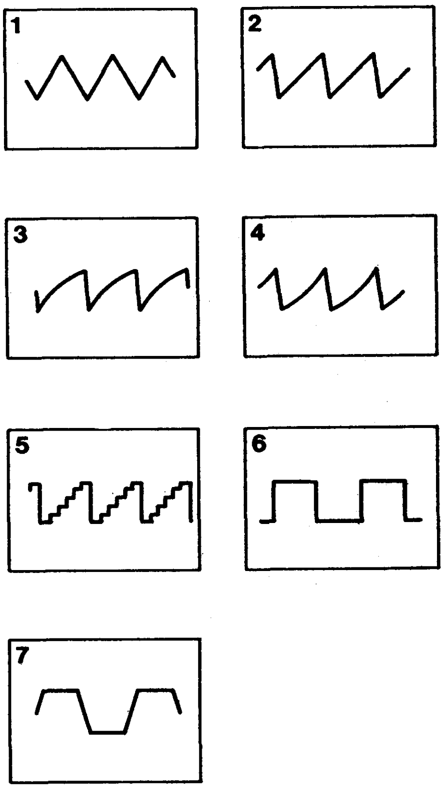
Flyback duration is determined by the rapidity with which the charge may be withdrawn from the capacitor, i.e. by the current capability of the discharge device/circuit. Perhaps the simplest device having a well-defined firing point, reasonably low leakage and satisfactory discharging capability is the unijunction transistor. With the so-called programmable unijunction device, which is internally more akin to a thyristor, a wide variety of circuits has been devised with linearity and definition of end points of around 1%. Constant-current sources are used to achieve linearity. Recent developments have included integrated circuits consisting of comparators, bi-stables and switching transistors, which though designed as timing circuits can produce similar waveforms. All such circuits suffer from the disadvantage that the load current flows in the charging circuit, disturbing the linearity.

If the capacitor is placed in the feedback path of an amplifier, as in the integrator due to Blumlein, though now more often called the Miller integrator, then a constant current may flow in the capacitor without load current disturbing that flow. This method is widely used in the circuits of the following section.

Triangular wave generator

The slopes of a triangular wave generally have equal positive and negative values, giving a symmetrical waveform. If desired, inequality may be introduced which if great enough yields an asymmetry that results in a near-sawtooth waveform. Combining an integrator of this type, often using an i.c. operational amplifier, with a Schmitt trigger (see series 2 Circards) both triangular and square waves are produced: a positive output from the Schmitt trigger drives the integrator to produce a negative-going ramp that in turn reverses the trigger output at some defined potential. Asymmetry is introduced by varying the effective input resistance of the integrator on the output swing of the trigger circuit for the two sections of the cycle. Control of the triangular wave amplitude is by means of the trigger-circuit input switching levels.

There are many applications which require voltage control of the frequency, e.g. remote programming, frequency modulation, amplitude-frequency response testing. To achieve this, the output of the



These waveshapes illustrate those dealt with in series 3 of Circards, being triangular (1), sawtooth (2), 'exponential' (3), over-compensated (4), staircase (5), rectangular (6) and trapezoidal (7) waveforms.

square-wave circuit is used to reverse the charging current, rather than feeding the integrator directly, leaving the magnitude of the current controlled by some external voltage or current source. Several methods are possible. An inverting amplifier provides a second voltage of equal magnitude but opposite sign to the control voltage, and the square wave activates electronic switches such as f.e.ts to select these opposite-polarity voltages alternately. Amplifiers may be designed in which the gain can be switched from positive to negative leaving the magnitude of the output again proportional to the controlled source. Finally, the integrator itself may be designed so that the switching is achieved directly, the current flow being reversed within the integrator.

In all these approaches the accuracy with which the frequency tracks the applied voltage depends on the switch. It should have that legendary performance of zero on-resistance and infinite off-resistance. Field-effect transistors, both junction and insulated gate, come close to achieving the latter parameter, but the low-cost units have on-resistances high enough to introduce errors, though first-order compensation by a deliberate unbalancing of the symmetry control could be used. In other cases bipolar transistors or even diodes are applicable, while for the highest accuracy more complex switches involving pairs of complementary f.e.ts provide a solution.

Square/trapezium generators

A square-wave output is an integral part of many triangular-wave generators. Rise-time is defined by the particular op-amp or comparator used, while the amplitude may approach supply voltage levels (though saturation effects are significant at lower supply voltages). By applying the square wave to a second integrator with sufficient over-drive, a trapezium wave, Fig. 7, with defined amplitude and variable-slope rising and falling edges results. The slopes may again be independently controlled if the drive conditions differ for the positive and negative portions of the input.

Staircase generators

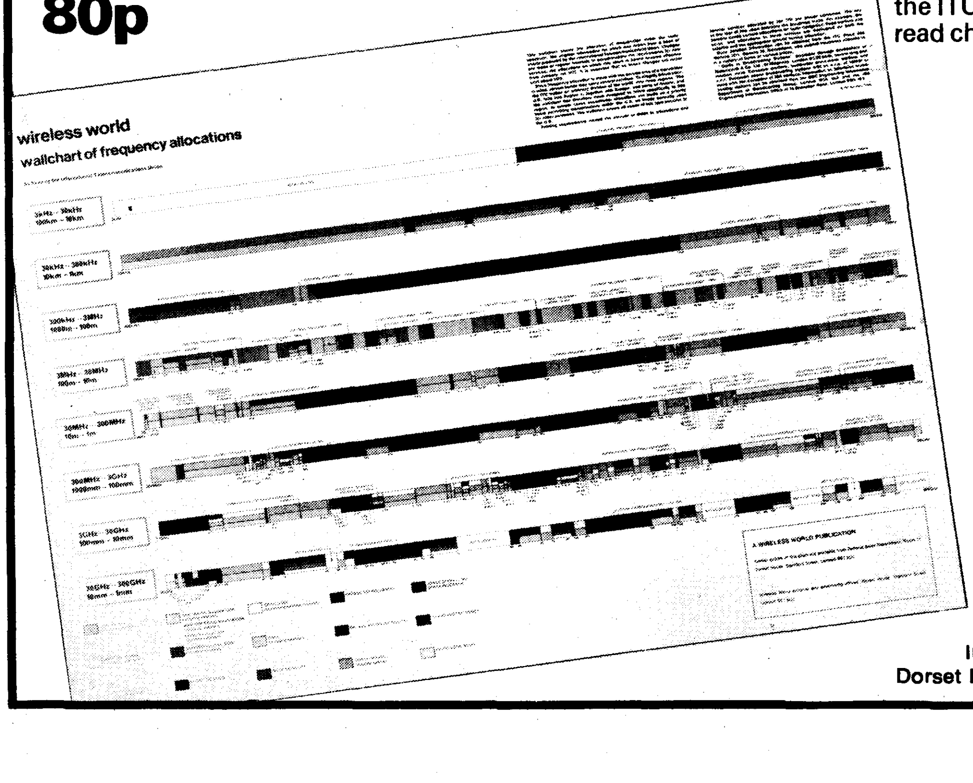
The diode pump is the classic circuit for obtaining a stepped output waveform that approximates to a linear ramp when the steps are of equal height and provided there is no change in amplitude during the interval between the steps. This implies that the capacitor should not discharge appreciably between input pulses and puts a lower limit on the repetition rate for any given circuit. To maintain equal step size at all outputs, amplifiers may be introduced to provide functions similar to bootstrapping as in the ramp circuits. This brings with it the upper frequency limit of the amplifier.

Digital-to-analogue converter methods extend the amplitude response down to d.c., with high accuracy also available, and an indefinite variety of wave-shapes that can be synthesized by selection of suitable resistor values.

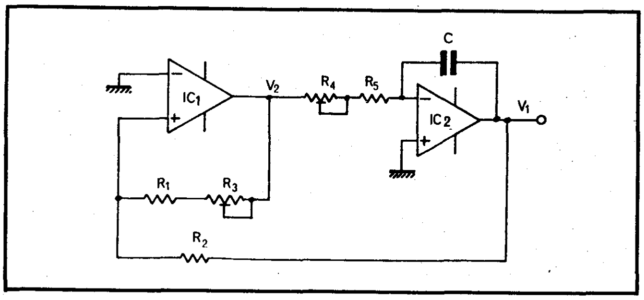
Wave-shaping circuits

In waveform-shaping circuits the options are very wide and the topic requires separate treatment, but some simple methods of shaping a triangular wave into an approximate sine wave can be suggested. In a see-saw amplifier the gain can be reduced as the magnitude of the input increases in two distinct ways, each of which gives a rounded peak to the output when fed by a triangular wave. The first method places a f.e.t. in the input with its increasing slope resistance at high amplitudes, while the second uses p–n diodes across the feedback network.

A second type of shaping involves the use of a switch to reverse a given waveform at some point in the cycle. This technique can be used to convert triangular waves into saw-tooth waves for example.



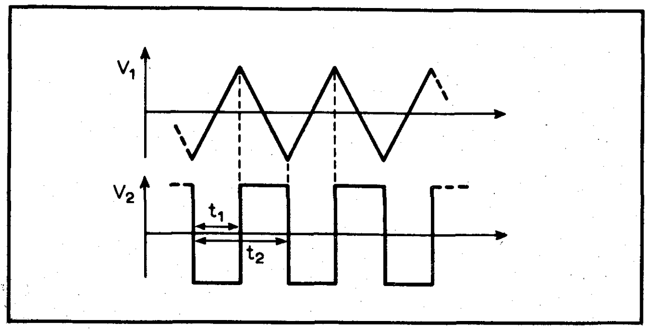
Basic op-amp square/triangle generator



Data

IC_1, IC_2: 741
Supplies: ±6 to ±15V
V_2: ±0.9V
V_1: 1 to 20V pk-pk

Frequency: zero to 3kHz
R_1: 10kΩ; R_2: 8.2kΩ
R_3: 1MΩ; R_4: 220kΩ
R_5: 1.2kΩ; C: 0.1μF



Circuit description

When a positive voltage is applied to the input of the inverting integrator, consisting of R_4, R_5, C and IC_2, the current flow causes C to charge, with its input end positive w.r.t. its output end. Negative feedback through C and the high gain of the amplifier jointly ensure that the inverting terminal retains a potential very close to that of the non-inverting terminal. The output must therefore go negative and provided the amplified input current is much less than the constant current in R_4 and R_5 the output voltage rises linearly with time. At some value of V_1 the negative current fed back through R_2 will overcome the positive current in R_1 and R_3, and the resulting negative current in the non-inverting input of IC_1 initiates a negative going transition in V_2. This allows the negative current in the non-inverting input to further enhance the output swing by this positive feedback action. The integrator output then reserves its slope and eventually becomes positive and finally switches V_2 back to its original positive value. Hence V_2 is a square wave and V_1 a triangular wave. Resistor R_4 gives independent frequency control and R_3 varies the frequency and the magnitude of V_1.

Component changes

- The low frequency of operation of this circuit is due mainly to the limited slew-rate of a 741 op-amp as the active element IC_1. A 301 op-amp will permit frequencies of up to 10kHz to be achieved, the square wave degenerating visibly before the triangle.
- R_1 and R_5 limit the current drawn from IC_1 when R_4 and R_3 are in their minimum positions and could possibly be omitted.
- R_2 may be varied widely but must not be so low that IC_2 is heavily loaded and not so high that IC_1 fails to switch before IC_2 reaches saturation.
- C can also be changed, bearing in mind that the slope of the triangle is inversely proportional to $C(R_4 + R_5)$.

Circuit modifications

- The triangular wave can be given a d.c. offset of either polarity by applying a bias signal V_6 as shown left in which R_6 = 10kΩ. The bias can be increased to the point at which the integrator saturates without changing the state of IC_1.
- A sawtooth waveform can be achieved by adding a d.c. signal V_3 to the integrator output, as shown middle. The magnitude of V_3/R_7 must be less than $[V_2/(R_5+R_4)]$ otherwise the integrator output will not change direction as V_2 changes sign. Time t_1 is greater than $t_2/2$ if V_3 is positive and t_1 is less than $t_2/2$ if V_3 is negative. The ratio V_3/R_7 must be comparable to $V_2/(R_5 + R_4)$ if a large mark-space ratio is required. Independent frequency control through R_4 is lost when this is done but may be regained by varying C.
- A sawtooth waveform can also be produced by the circuit, right, which does not require an external signal. Any general purpose diode will do. With the diode as shown $t_1 < t_2$, but $t_1 > t_2$ if the diode is reversed. As shown, the integration rate on the negative-going side of the triangle is controlled with $R_4 + R_5$ and on the positive-going side by R_8 in parallel with $R_4 + R_5$.

- The output of IC_1 may be clamped to a well-defined level by inserting a series resistor in the output lead and taking a pair of back-to-back zener diodes to ground. This produces a better defined integration rate and makes t_1 more nearly equal to $t_2/2$. Drive point for the circuits is taken as the junction of the resistor and zeners. Clamping on many i.cs is possible at low signal levels by means of terminals on the i.cs (cross ref. 2).

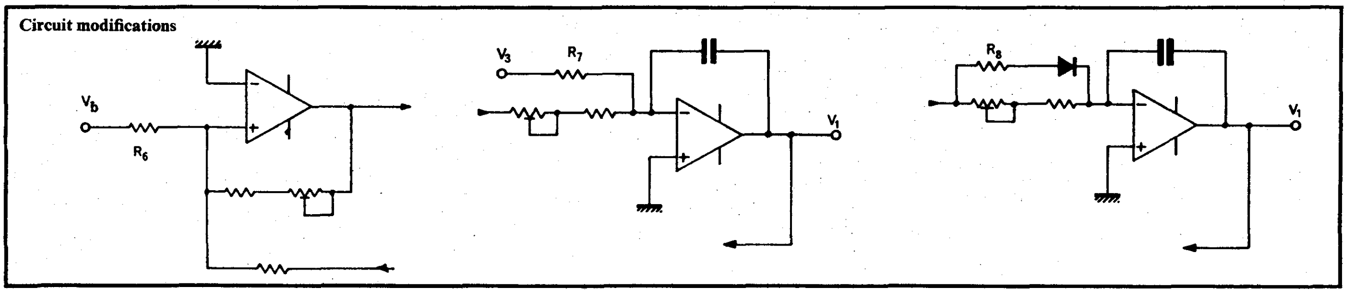
Further reading

Clayton, G. B. Triangular square wave generator *Wireless World*, vol. 75, 1969, pp.586/7.
Tobey, G. E., Graeme, J. G. & Huelsman, L. P., Operational Amplifiers, McGraw Hill 1971, pp.373-81.
Linear Applications Handbook, National Semiconductor application note AN31-6, 1972.

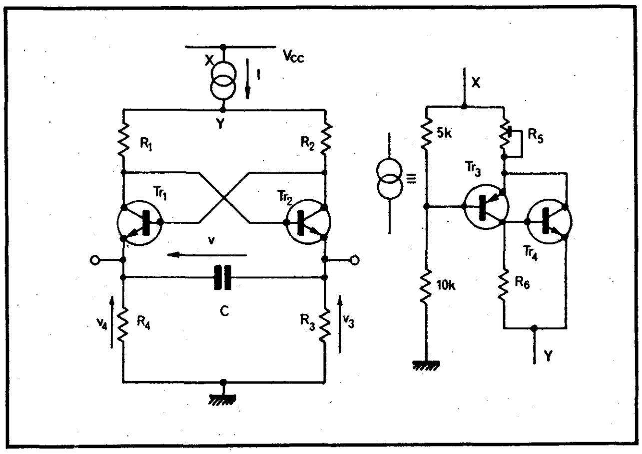
Cross references

1 Series 3 cards 2 & 11.
2 Series 2 cards 1 & 3.

Circuit modifications



Emitter-coupled triangular wave generator



Typical performance

Tr$_1$, Tr$_2$, : BC125
Tr$_3$: BC126
V_{CC}: +15V
C: 0.1μF
R$_5$: 2.2kΩ
R$_1$, R$_2$: 330Ω
R$_3$, R$_4$: 4.7kΩ
R$_6$: 10kΩ
f: 5.3kHz
$f \propto 1/C$

$v_3 = v_4$: Antiphase triangular waveforms 0.4V pk-pk on a d.c. level of 4V. As R$_5$ is reduced, d.c. level rises towards 8V; frequency increases to 7kHz, as long as triangular waveform is maintained. A ramp voltage at $2f$ is available at Y.

Circuit description

The circuit is an emitter-coupled astable circuit normally fed from a voltage source. This results in sharp transistions in the voltages across R$_3$ and R$_4$ at the circuit switching points. These can be eliminated by driving from a constant-current source, so that only the direction of charging current in capacitor C is reversed, the magnitude varying little throughout the cycle. Consider Tr$_1$ fully conducting, Tr$_2$ off. The charging circuit is then as shown in the above diagram. Provided the conditions $v < v_3$ and $v \ll v_4$ are maintained, the capacitor charges linearly, but in any case for $R_3 = R_4$, any rise in v_4 must be accompanied by an identical fall in v_3, to maintain a constant total current. Hence there are two outputs v_3 and v_4 which are of identical shape but anti-phase, and are also good approximations to triangular waveforms. The transition will occur in the above example when $v \approx -0.5$V at which condition Tr$_2$ begins to conduct, positive feedback rapidly completing the transition. Increasing the source current increases the charging rate, and hence frequency, with little change in amplitude. The output has an amplitude of ~1V pk-pk at a mean level of ~ 5V, depending on the controlled supply current. Supply current is defined by the constant-current source connected between X and Y, where R$_5$ determines the value of I.

Component changes

Useful range of C: 1μF to 3.3nF
Frequency range: 0.5 to 130kHz
A 20% reduction in V_{CC} varies frequency by about 5%.

Circuit modifications

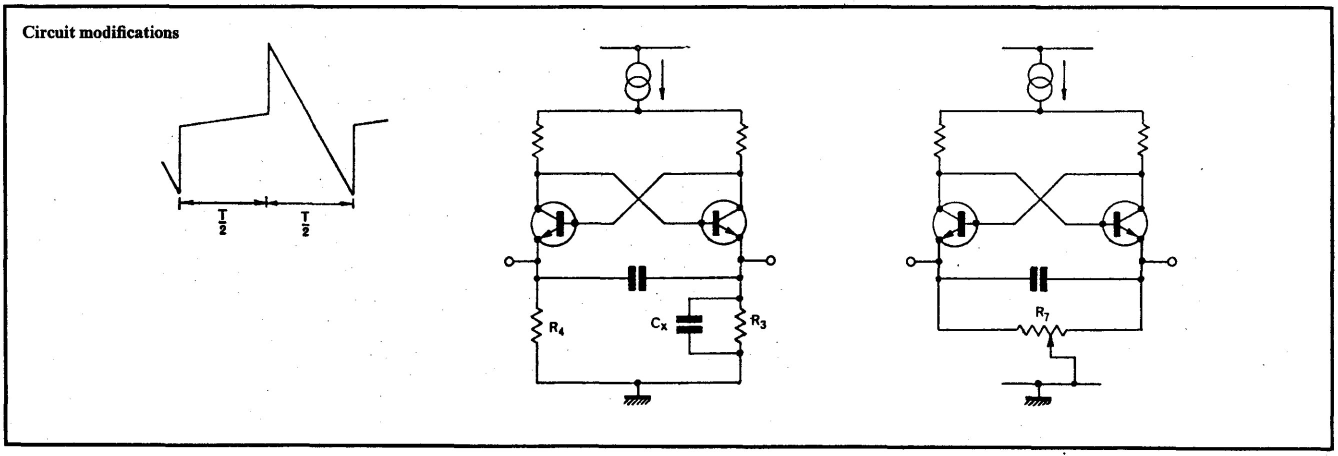
- With $R_5 = 0$, $C = 0.1\mu$F, a condition arises where the drive is not from a constant-current source, but the circuit is connected as an oscillator with d.c. supply ≈ 15V. The shape of the output waveform is then as shown left which has a d.c. level of 11V and a swing of 6V pk-pk.
- Voltage spikes occur at the positive and negative peaks of the normal triangular waveforms, due to the change in p.d. across the oscillator causing sharp current spikes from stray capacitance existing across the oscillator; i.e. circuit is temporarily operated from a constant voltage rather than a constant-current source. These can be eliminated by connecting capacitor C$_x$ in the range 3 to 10C, as shown middle. Typically, for $C = 0.1\mu$F, $R_5 = 2.2$kΩ, $C_x = 1\mu$F. The waveform across R$_4$ is doubled, the frequency change being < 1%.
- Resistors R$_3$ and R$_4$ replaced by a 10-kΩ potentiometer R$_7$ as shown right. As R$_7$ is varied, the output triangular wave peak amplitude remains unchanged, though the slopes alter assymetrically. Typically for $C = 1\mu$F, $R_5 = 2.2$kΩ, $f = 0.5$kHz when R$_7$ is set at mid-point. For a setting of 2:1, frequency reduces by 10%.

Further reading

Hemingway, T. K. Electronic Designer's Handbook, Business Publications 1966, pp.191-4.
Transistorized all-waveform generator, in Electronic Circuit Design Handbook, Tab 1971, p.252.

Cross references

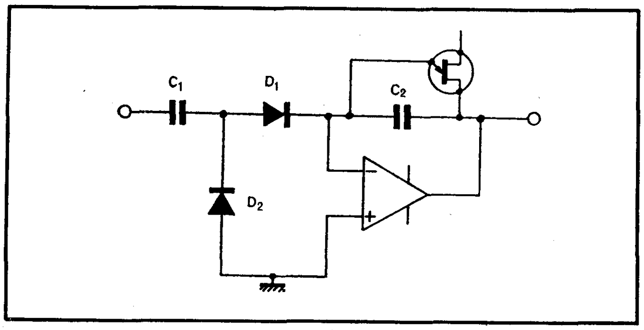
Series 3 card 1.


Circuit modifications

Wireless World Circard

Series 3: Waveform generators 3

Diode-pump staircase generator



Typical performance

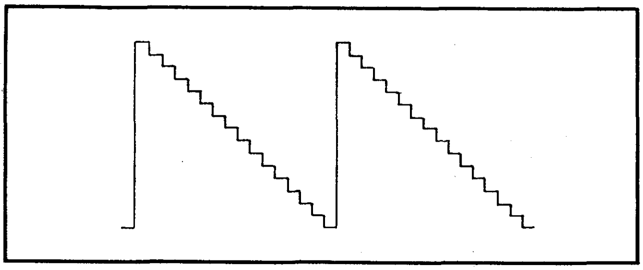
IC: 741
Tr: 2N2160
C_1: 3.3nF±10%
C_2: 3.3nF±10%
D_1, D_2: 1N914
V_{in}: +3.6V pulses
repetition rate: 1kHz
pulse width: 200µs
Output step ~ 0.28V
Ramp height ~ 8V
No. of steps ~ 28

Supplies: ±15V
V': +4V

$$\text{Step size} \approx \frac{(V_{in}-1)\,C_1}{C_2}\cdot V$$

$$\text{No. of steps} = \frac{\text{height}}{\text{step size}}$$

Ramp height dependent on unijunction but ~2V'



Circuit description

The basic diode pump has diode D_2 feeding capacitor C_2 (grounded), and without the amplifier. On the first positive input pulse D_1 conducts and provided the pulse duration is long enough the pulse amplitude is shared between C_1 and C_2 -the same charge producing the larger portion of the p.d. across the smaller capacitance. On each succeeding pulse the p.d. established across C_2 opposes any fresh flow of charge, and the step in the output voltage diminishes progressively to zero when the p.d. across C_2 equals the input pulse amplitude. In the circuit shown, the amplifier virtual earth prevents the p.d. across C_2 from influencing the charge flow on successive cycles and the p.d. builds up in equal steps. In each case the charge acquired by C_1 during the pulse is lost to ground through, D_1 when the input returns to zero i.e. C_1 commences each cycle in an uncharged state. Departures from the ideal are: p.d. across each diode when conducting is ~ 0.6V for silicon, reducing the effective input pulse amplitude by ~ 1.2V; amplifier input draws a small but finite current that adds a continually varying output due to integration via C_2; to make the circuit free-running a device such as a unijunction transistor must be added to provide periodic discharge of C_2, and such devices contribute additional leakage currents.

Component changes

C_1: 100pF to 1µF
C_2: 100 pF to 1µF
D_1, D_2: general-purpose Si diodes
IC: any general-purpose compensated op-amp e.g. 307.
V_{in}: 1 to 20V pk

Pulse rise time should not be too small a fraction of pulse width or excessive transient currents appear at amplifier input.
Pulse width: < 1µs to > 1s
Mark/space ratio: 1:100 to 100:1
Repetition rate: 1Hz to 100kHz.

Circuit modifications

- Use of bootstrap technique returns r.h. end of C_1 to output through D_2 at end of each positive pulse. This ensures that on next positive pulse D_1 begins to conduct at start of pulse even if p.d. across C_2 and hence at output is greater than pulse height in. Ramp steps of constant size and ramp height limited only by amplifier. Again unijunction may be used to end ramp. (left)
- An alternative range of transistor-pump circuits may be devised. On the positive edge, D_1 conducts and C_1 and C_2 charge with p.d. shared between then in inverse ratio to capacitance. On negative edge, Tr_1 conducts clamping C_1 to just below output while discharging C_2 only by base current of Tr_1. (middle)
- An alternative form of bootstrap circuit comparable to first modification (right) with emitter follower replacing voltage follower.

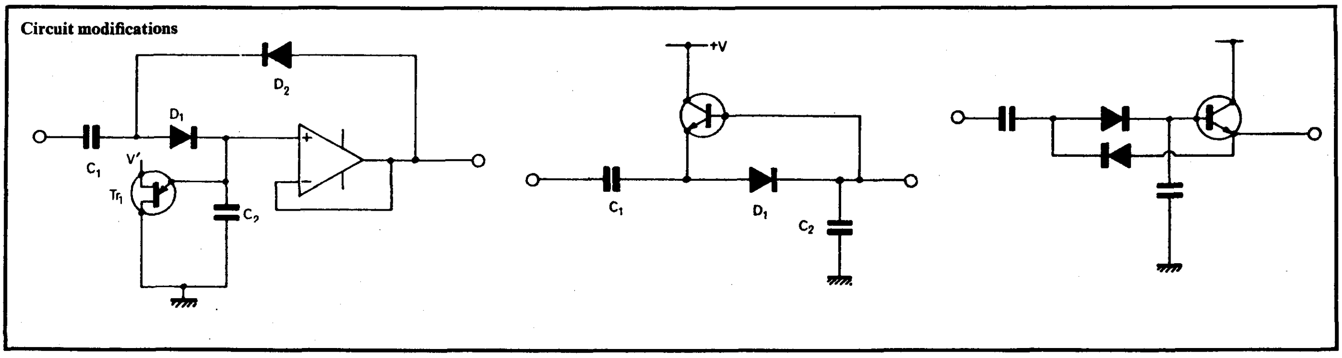
Further reading

Hemingway, T. K., Electronic Designers Handbook, Business Publications 1966, pp.215-24.
Staircase wave generator, in GE Transistor Manual, 7th edition, p.345.
Clayton, G. B., Resistive feedback networks, *Wireless World*, Aug. 1972, pp.391-3.

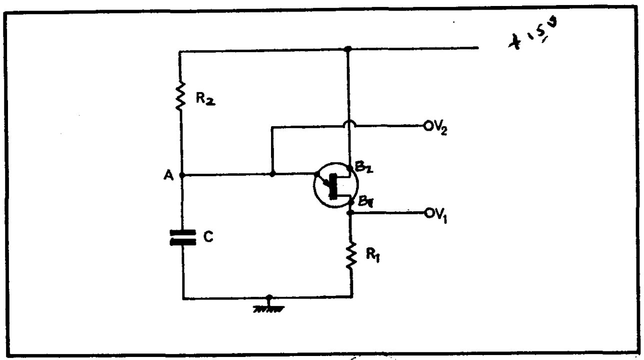
Cross references

Series 3, cards 4 & 5.

Circuit modifications



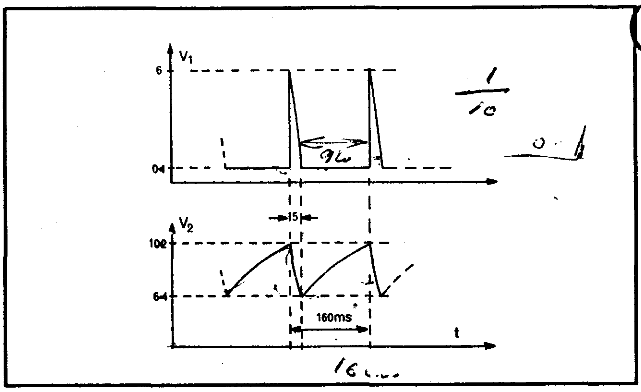
Unijunction sawtooth generator



Data

Typical output waveforms obtained with
R₁: 100Ω ± 5%
R₂: 10kΩ ± 5%
C: 1μF ± 5%

V : +15V
Tr: 2N2160
Supply range can be 4 to 20V at least.



Circuit description

Circuit is used as a sawtooth (V_2) or a trigger pulse generator (V_1). Capacitor C charges through R₂ until the unijunction transistor V_p is reached and then discharges via R₁ until the transistor changes state at approximately $0.5V_E$(sat); C then starts charging through R₂ again. Waveform frequency $\propto 1/R_2C$. With R₂ fixed at 10kΩ and C varied, the waveform details (apart from the period) remain identical as C is reduced down to 220 nF. At 10nF, V_1 is reduced to half its previous value and the pulse width increases to approximately 1/10th of the period. At 1nF the pulse height is further reduced and V_2 becomes rounded.

Emitter leakage current modifies the charging waveform and places an upper limit on the value of R₂ for guaranteed operation. The firing potential is temperature dependent because of the p-n junction p.d. at the emitter junction. This leads to temperature-induced frequency instability which can be compensated for by the insertion of a small series resistor in series with B₂. The rise in the B₁, B₂ path resistivity with temperature reduces the current and hence the p.d. across this resistor, leaving a larger part of the supply voltage at the junction.

Component changes

Reduction of R₁ to zero causes V_1 to become zero but has little effect on V_2. Any standard unijunction transistor may be used. Motorola 2N2646 will produce a smaller lower limit on V₂ and consequently reduced frequency for the same C & R.

Circuit modifications

- Discharge time through R₁ may be greatly reduced by the modification, shown left, in which V_2 is used to short the capacitor to ground. This makes the pulses of V_1 much narrower and alters the frequency slightly.
- The unijunction transistor may be replaced by the two transistor version, shown middle, with R₁ 100Ω, Tr₃ BC126, Tr₄ BC125 and the potentiometer 2.2kΩ. The lower value of V_2 in this case comes much closer to zero. The potentiometer is set to the maximum value of V_2 required plus V_{be}.
- Circuit shown right may be attached to any of the circuits to remove the error arising when the supply is switched on, at which point V_2 is at 0V rather than the minimum value it later achieves on the first discharge cycle. Resistors R₅ and R₆ are chosen so that the transistor conducts, charging C rapidly to this minimum value (ref 2).
- Charging resistor R₂ can be replaced by a defined current source e.g. a constant-current source will produce a linear ramp instead of an 'exponential', (Circards, series 3, card 2).

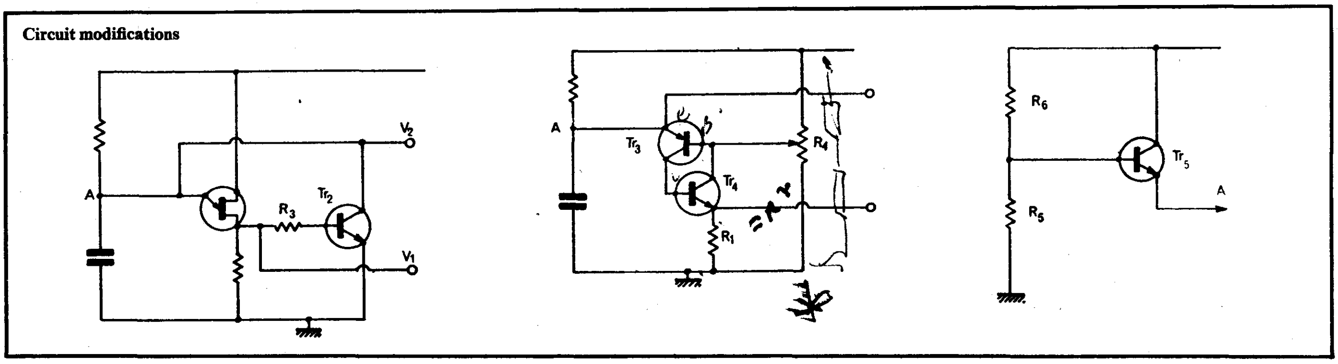
Further reading

1 Ultra-linear ramp generator uses UJT to drive Darlington, in 400 Ideas for Design, Hayden, p.119.
2 Electronic Circuit Design Handbook, Tab 1971, p.173.
3 Triac, UJT & FET give linear ramps, in 400 Ideas for Design, Hayden, p.128.

Cross references

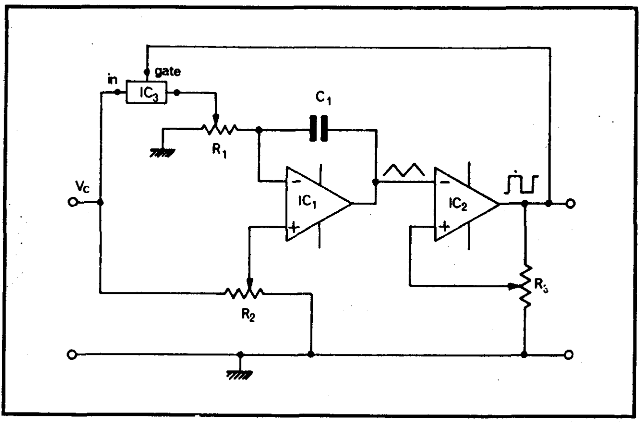
Series 3, cards 2 & 8.

Circuit modifications



Wireless World Circard Series 3: Waveform generators 5

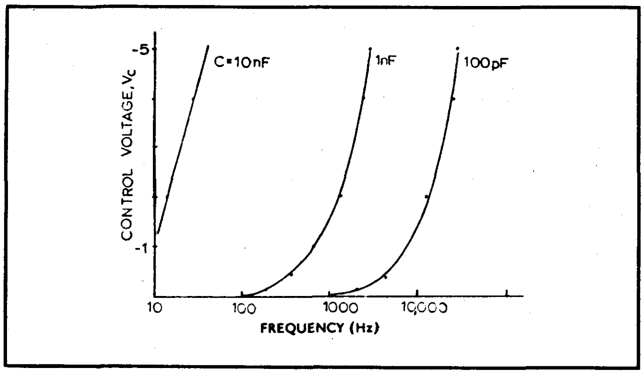
Voltage-controlled square/triangle generator



Typical performance

IC$_1$: 741
IC$_2$: 301
IC$_3$: $\frac{1}{4}$ (CD4016)
Supplies: ±1V
Control voltage, V_C: −1V
Frequency: 660Hz
Square wave: 8V pk-pk

Triangular wave:
4V pk-pk
C$_1$: 1nF
R$_1$, R$_2$: 100kΩ (mid-position)
R$_3$: 10kΩ



Circuit description

The basic idea of an integrator feeding a schmitt trigger may be adapted to allow voltage control of oscillator frequency. The square wave output of IC$_2$ controls on electronic switch IC$_3$ (in this case a c.m.o.s. transmission gate) which operates directly on the integrator without need for an additional reversible gain amplifier. A fixed portion of the control voltage is applied to IC$_1$ non-inverting input through R$_2$, while the tap on R$_1$ is alternately open-circuited and connected to the input. With the switch closed, the inverting input receives a negative current as the full input is applied via part of R$_1$ to the inverting input, while the non-inverting input is held at some fraction of V_C. For an open switch the inverting input is returned to ground via R$_1$ while the inverting input is still maintained at a constant negative voltage. A convenient setting, if the switch is ideal, is for R$_1$ to be centre-tapped with the non-inverting input tapped onto R$_2$ at $\frac{2}{3}V_C$. Either can be replaced by corresponding fixed resistors with the other varied to obtain best symmetry i.e. compensating for finite on resistance. The Schmitt circuit is conventional while the particular switch may be replaced by any switch that can connect the slider of R$_1$ to V$_c$.

Component changes

- Frequency is linearly related to control voltage V_C up to −4V.
- Useful range of Cl: 100 pF to 0.1 μF.
- Positive feedback via R$_3$ must be <75% to maintain triangular shape, because of saturation of the IC$_1$ for the low supply voltage used.
- Adjustment of R$_2$ controls the mark/space of the square wave and slopes of the triangular wave, without altering the amplitude. Typically, C = 1nF V_C = −4V, mark/space can be 1:15 at f = 1250Hz to 17:1 at f = 460Hz.

Circuit modifications

In the circuit shown left, the basic form of the integrator and Schmitt circuit remains the same, but the electronic switch now operates in a shunt mode. A simple analysis to indicate appropriate potentiometer settings to ensure symmetrical triangles is shown above. Note that the control voltage is now positive with respect to ground. The linear relationship between V_C and f is indicated right for C = 1nF, n = 1, $k = \frac{1}{3}$ and a supply of ±5V.
Triangular output is 4V pk-pk. Operation at 1Hz is easily achieved, but some readjustment of R$_2$ necessary to retain symmetry. Effect of supply voltage on frequency for the above components is also indicated.

Further reading

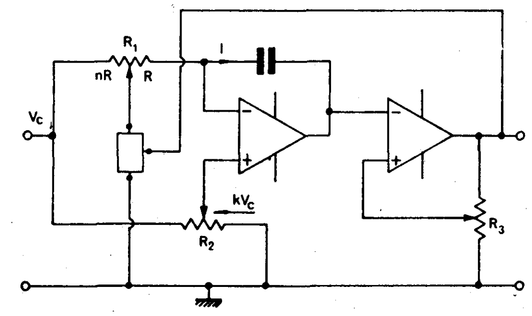
LM311 Voltage Comparator. National Semiconductor data 1970.

2 Tidley, R. J., Voltage-controlled triangle/square generator, *Wireless World*, May 1972, p.239.

Cross references

Series 3, card 11.

Circuit modifications



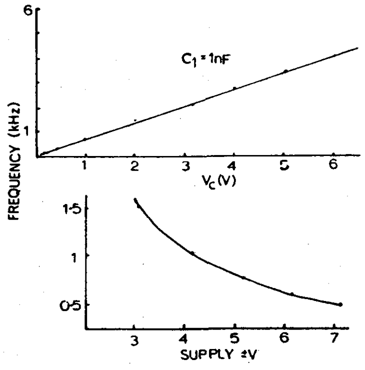
For switch open $I = \dfrac{V_C - kV_C}{(n+1)R}$

For switch closed $I = \dfrac{-kV_C}{R}$

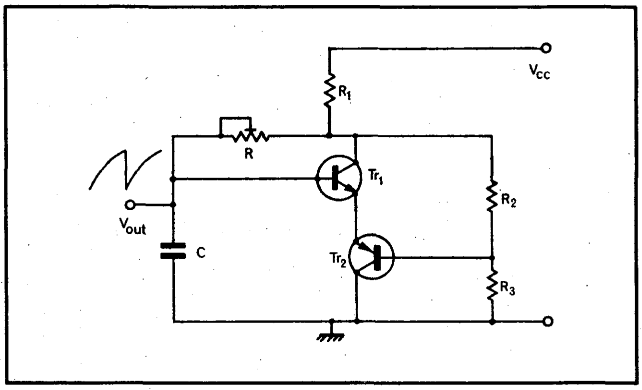
For equal slopes: $(n+1)k = 1 - k$

$$n = \frac{1}{k} - 2$$

$\therefore$ For $n = 1 \quad k = \frac{1}{3}$.



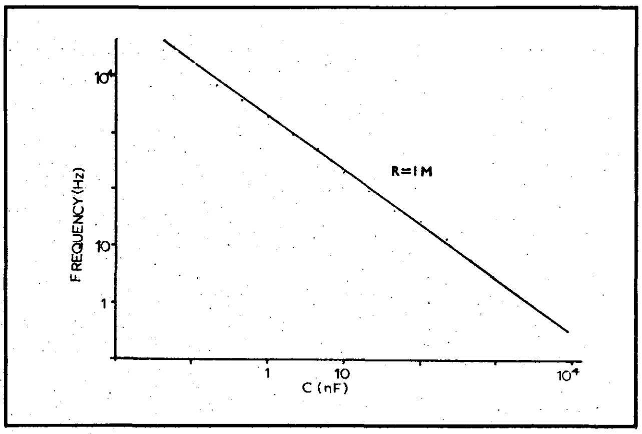
Complementary transistor sawtooth generator



Typical performance

V_{CC}: +15V
Tr_1: BC125, Tr_2: BC126
R_1: 2.2kΩ, R_2: 22kΩ
R_3: 15kΩ, R: 1MΩ (pot)

C: 10nF
V_{out} excursion is 2.8 to 7V at 1kHz.
Supply current: 0.5mA



Circuit description
This circuit is related to the corresponding trigger circuit described in Circards series 2. Consider the capacitor in an initially uncharged state. The base potential of Tr_1 is zero and no current flows in either Tr_1 or Tr_2. The p.d. across R is a large fraction of V_{CC} provided the current in it and in the potential divider are small enough to avoid a large drop across R_1. As the capacitor charges the p.d. across R falls and with it the rate of charge. When the potential at the base of Tr_1 exceeds that at the base of Tr_2 by ~1V the transistors begin to conduct. This reduces the potential at Tr_2 collector and at the base of Tr_2 through the potential divider. The increased p.d. between the bases that results completes the positive feedback action, ensuring a rapid switching, with the p.d. across the capacitor falling to a low value (determined by the saturation characteristics of Tr_1). Similarly the potential at Tr_1 collector falls. After the switching transient, the recharging cycle begins. Returning R to the collector rather than V_{CC} provides negative feedback that reduces risk of circuit latching into permanently stable d.c. state.

Component changes
Minimum V_{CC} = 4V, oscillation ceases at 3.4V. With C = 1nF, $R_{min} \approx 47k\Omega$, $R_{max} \approx 2.6\ M\Omega$. Useful range of C: 47pF to 32μF (tantalum bead). Maximum useful frequency ≈ 70kHz.
Changing the ratio R_3/R_2 alters the voltage to which C charges.

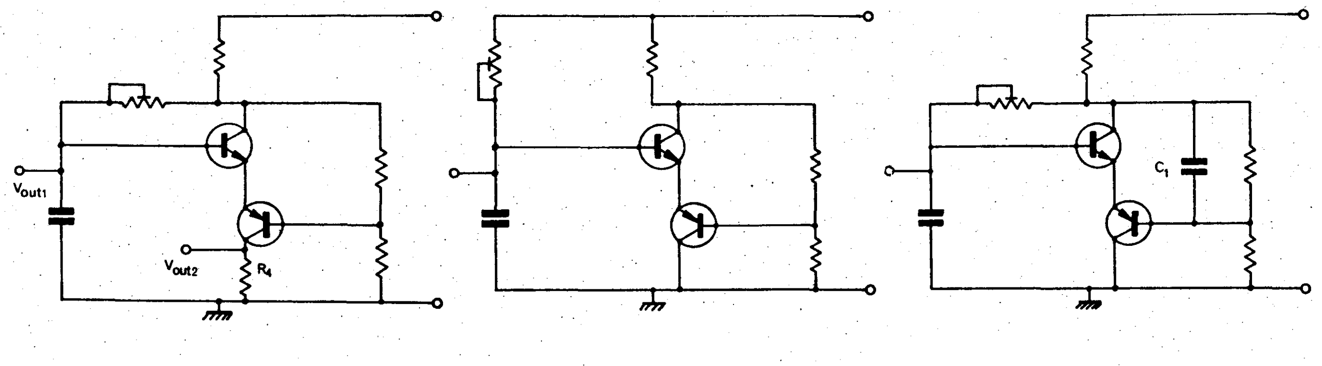
Circuit modifications

- A resistor may be included in Tr_2 collector (R_4 in Fig. on left) to provide a train of narrow pulses typically of amplitude 0.6V when R_4 = 100Ω. Anti-phase pulses, of amplitude ≈ 14V are available at Tr_1 collector.
- Resistor R may be returned to the V_{CC} rail instead of Tr_1 collector, as shown middle. To increase R above 2.6MΩ, current gain of Tr_1 could be increased by replacing it with a Darlington unit.
- Speed-up capacitor C_1 may be added, as shown right, to increase the maximum repetition rate.
- The complementary pair may be replaced by a BFR41-BFR81 pair and all resistors can be scaled down by a factor of about ten to give higher current operation, for example, larger output pulses at R_4. A V_{CC} up to about 90V may then be used.

Further reading
Electronic Circuit Design Handbook, Tab 1971, pp.172 & 184.
Cairns, J. B. F., Linear ramp generator, *Wireless World*, vol. 77 1971, p.604.

Cross references
Series 2 card 12.
Series 3 card 9.

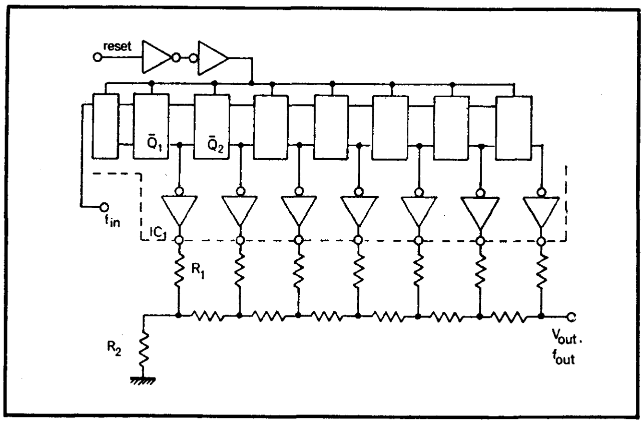
Circuit modifications



Wireless World Circard

Series 3: Waveform generators 7

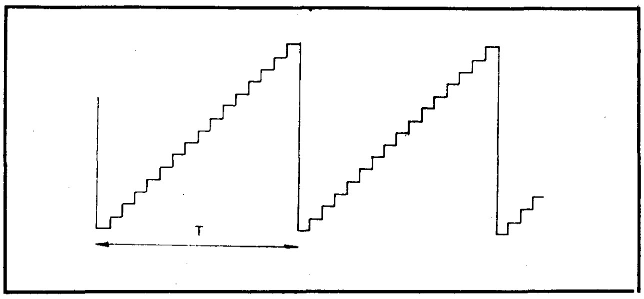
D/A convertor waveform generator



Typical performance

IC_1: CD4024A
Supply: + 5V
R_1: 94kΩ
R_2: 47kΩ
f_{in}: 12.8kHz
f_{out}: 100Hz i.e. for waveform shown, T = 10ms.

For a 7-bit counter, waveform comprises 128 steps.
Minimum input level: 1V
Minimum input pulse: 3.5μs



Circuit description

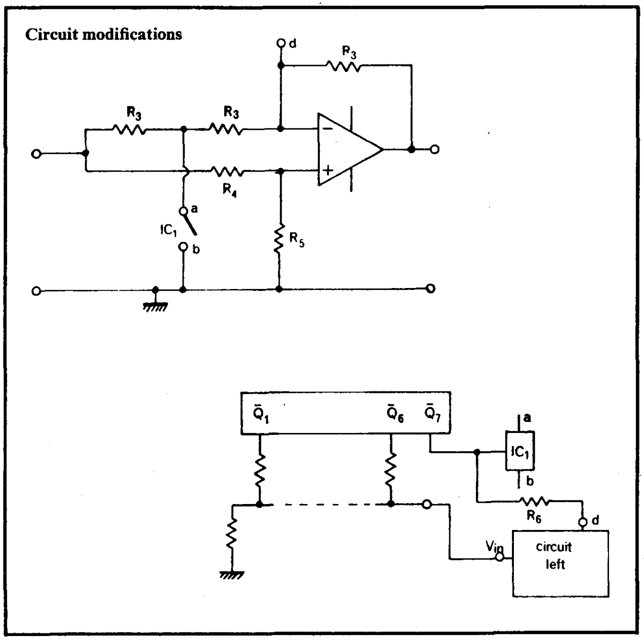
If the output of a binary counter is used via buffer stages to drive a resistor network, a stepped output voltage is obtained which repeats for each cycle of the counter. If the counter is clocked at a definite frequency then the output frequency is fixed by the division ratio introduced by the counter. If the clock rate is variable so is the output voltage with no change in wave-shape, while modifying the network changes the shape without affecting the frequency. The circuit shown is one example where a seven-stage binary counter feeds a resistive ladder network. The buffer elements are contained within the IC package and provide a drive voltage which is accurately defined for light loading. Using identical resistors along the chain, the change from logical '0' to logical '1' at Q_1 causes a change at the input to the ladder which is progressively attenuated, halving for each succeeding stage in the counter provided $R_1 = 2R_2$. Thus the least significant bit from the counter contributes only half the output contributed by the next bit. The result is an output voltage that is an analogue representation of the total number of bits stored in the counter, and for constant repetition rate and n stages, staircase waveform results with 2^n equal steps.

Component changes

Maximum useful output frequency: 1kHz, demanding an input p.r.f. of 128kHz. Minimum pulse level at this rate is 2V, though this varies ± 50% with package substitution. An output repetition rate of 0.01Hz is easily achieved. Minimum pulse level is linearly related to supply voltage variations in the range 5 to 10V.

Circuit modifications

An up and down staircase waveform may be generated by inverting each alternate cycle. A suitable inverting amplifier is shown top. Resistor R_3 is 33kΩ; IC_1: ¼ (CD4016) c.m.o.s. transmission gate. Resistors R_4 and R_5 are 100kΩ, R_4: 84kΩ and R_5: 16kΩ.
Diagram on bottom indicates the overall connection, where only six outputs from the counter are used to generate the staircase. The most significant bit-driving pulse is now used to switch both the c.m.o.s. gate and trigger the op-amp inverter. Resistor R_6 is 750kΩ for the above values of R_4, R_5.



Further reading

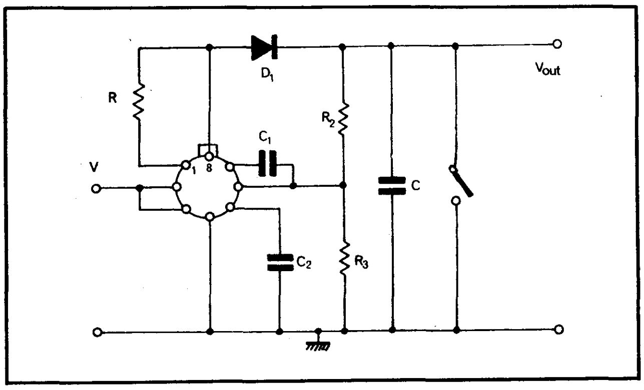
COS/MOS Digital Integrated Circuits, RCA, 1972, p.113.
Naylor, J. R., Digital and analog signal applications of operational amplifiers, *IEEE Spectrum*, May 1971, pp.82-4.
Staircase-wave generator uses integrated circuits, in 400 Ideas for Design, Hayden, 1971, p.111.
COS/MOS Integrated Circuits RCA, 1971, pp.72-81.

Cross references

Series 3, cards 3, 11 & 12.

Wireless World Circard Series 3: Waveform generators 8

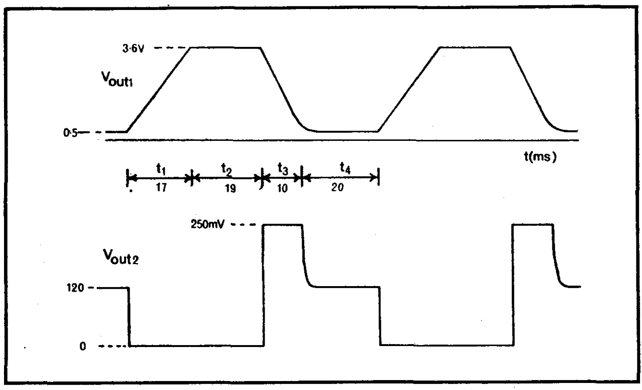
Triggered ramp/trapezium generator



Typical performance

Supply (V): + 10V
IC: LM305
R_1: 220Ω
R_2 R_3: 100kΩ
C_1: 47pF; C_2: 100nF
C_3: 22μF; D_1: SD2

With transistor version (over, left), where Tr_1 is BFR41, R_4 1kΩ, R_5 47Ω, V_p = + 1V, period is 66 ms, width is 30 ms, and source res. 50Ω; waveforms are typically as shown



Circuit description

A ramp with an accurately defined maximum value may be desirable for some applications. This can be provided simultaneously with good control of ramp slope, by using an i.c. voltage regulator having internal current limiting. At switch on, capacitor C_3 is uncharged and the switch is open. The regulator remains in its constant-current mode, charging C_3 until the p.d. across it produces a potential at the junction of R_2 and R_3 that matches the internal reference of the regulator. At this point the regulator reverts to its constant-voltage mode and the output voltage remains constant at a value that may be controlled by the ratio R_2/R_3. During the ramp, the current drawn by the potential divider increases as the p.d. across it rises and this, combined with variation in the current-limiting action at different load p.ds, gives rise to some non-linearity. For this reason R_2 and R_3 are increased though this marginally reduces output voltage stability. Any convenient means may be used to discharge the capacitor to initiate a following cycle and Tr_1 driven from a pulse source is one example.

Component changes

Maximum useful frequency ≈ 100kHz.

With R_3 equal to 100kΩ, variation of R_2 over the useful range 22 to 150kΩ varies V_{out_1} between 8.5 and 3V. Output voltage waveform becomes a ramp either when R_1 is increased to about 470Ω or C_3 increased to about 32μF.

With C_3 equal to 22μF, max. useful R_1 is about 10kΩ (ramp amplitude no longer defined by regulator feedback resistors R_2 and R_3).

With R_1 equal to 1Ω, max. useful C_3 value is about 3000μF.

With R_1 set at 220Ω, V_{out} becomes a square wave with C_3 of 1nF.

Output voltage waveform can be made triangular by adjustment of time constants, e.g. triangle is 1.2V pk-pk, clamped at 3.6V with R_1: 330Ω, C_3: 1000μF & R_5: 100Ω.

Circuit modifications

To give a higher output current rating and to provide a fold-back (negative resistance region) to the regulator, the circuit can be modified to the form shown in the middle diagram.

The waveforms shown right are typical of those obtained with the following V: +10V, R_1: 5Ω, R_2: 3.9kΩ, R_4: 1kΩ, R_5: 15Ω R_6 + R_7: 1kΩ, C_1: 47pF, C_2: 100nF, C_3: 1000μF, Tr_1: BFR41, Tr_2: BFR81, V_p: +3.6V. Period: 45ms, pulse width: 26ms, pulse source resistance: 50Ω.

With R_6 + R_7 equal to 1kΩ, R_6 should not be greater than about 200Ω to obviate excessive instability of the regulator due to the negative resistance characteristic. Lower level of V_{out} is less well-defined than its upper level due to dependence on V_{CE} (sat) of Tr_1 and V_p amplitude.

Further reading

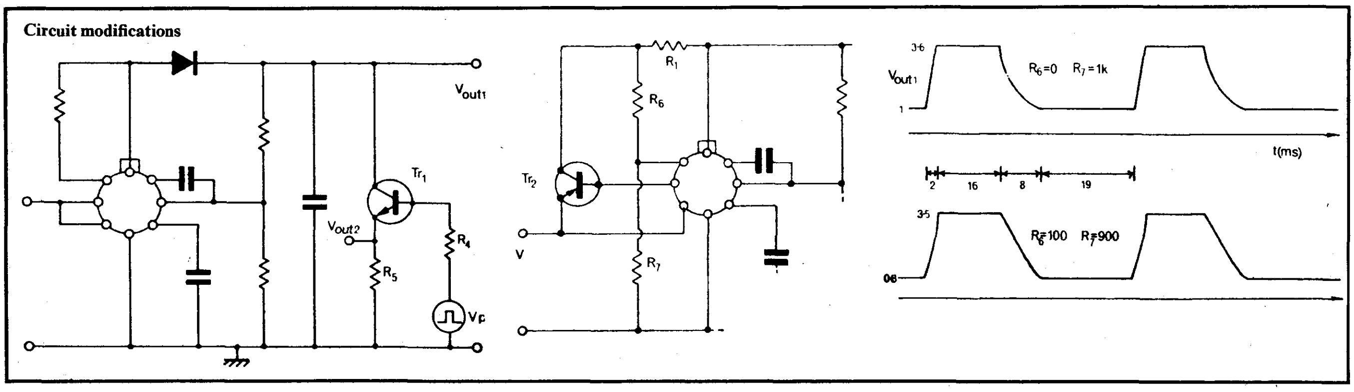
Elmgren, K., *Journal of Physics E: Scientific Instruments* (Letters), vol. 5 1972, p.296.

Linear Integrated Circuits Data Book, National Semiconductor 1971, p.31.

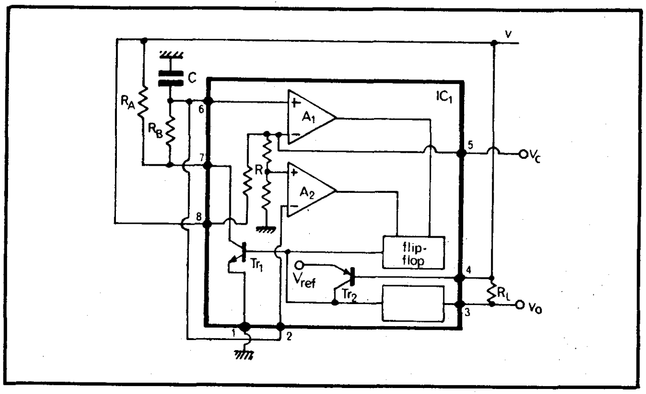
Cross reference

Series 3, card 4.

Circuit modifications



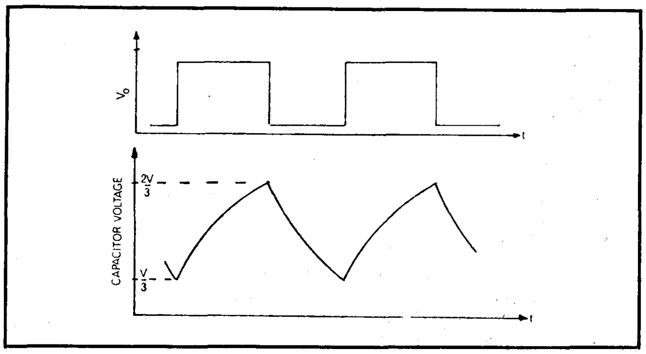
Stable waveform generator using single i.c.



Typical performance

IC: NE555V (Signetics)
V: +5V
R_A: 1 kΩ±5%
R_B: 100 kΩ±5%
C: 10nF±5%
f: 710Hz

Charge time ~ 0.69 × (R_A + R_B)C
Discharge time ~ 0.69 × R_BC
Period ~ 0.69(R_A + 2R_B)C
Duty cycle: R_B/(R_A + 2R_B)



Circuit description

The i.c. was designed as a versatile timer capable of operation in the astable mode. Frequency and amplitude of the waveform across the capacitor are very stable, and the waveshape can be modified by changing the charge/discharge circuit Consider the flip-flop in the state that leaves Tr_1 non-conducting. The capacitor charges through R_A + R_B until the high-level comparator reverses the flip-flop. Transistor Tr_1 conducts, discharging C through R_B until the low-level comparator returns the flip-flop to its initial state allowing the cycle to re-start.

For $R_B \ll R_A$ the flyback time is very short, and sawtooth waveforms are possible. Conversely for $R_B \gg R_A$, the time-constants for the two sections of the cycle become comparable. Comparator input currents are low and high values of R_A and R_B may be used without deterioration of the waveform or loss of timing accuracy. Capacitor waveform is defined by the comparator levels to lie between $V/3$ and $2V/3$.

Unless the load resistance is $\gg R_A$ and R_B, buffering of the output from the capacitor is required. A square pulse output is available which can supply load currents of > 100mA with respect to either supply line and without disturbing frequency. A reset function is available that over-rides the charging action and a control voltage that changes the comparators' reference potentials i.e. allows modulation.

Component changes

V: +4.5 to +16V
R_A: 1kΩ to 1MΩ
R_B: 1kΩ to 1MΩ
C: 100 pF to 100μF

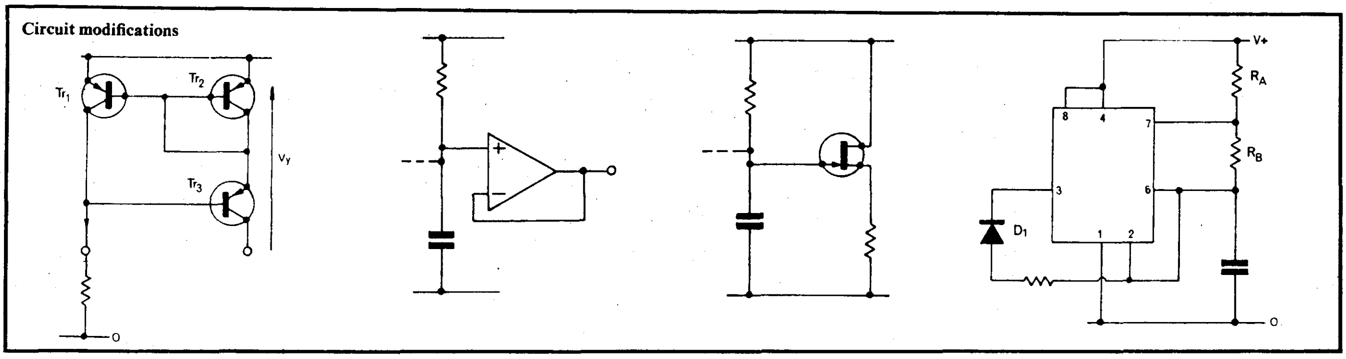
- Control voltage (pin 5) varies on and off levels in same ratio, allows modulation of frequency, but also changes amplitude of capacitor waveform.
- Addition of silicon diode in parallel with R_B, conducting on forward stroke makes charge time dependent mainly on R_A. Discharge still depends on R_B i.e. Duty cycle adjustable $\gtrless \frac{1}{2}$. Diode drop affects accuracy, particularly for low V.
- Output may be synchronized with external waveform fed to control input (pin 5) or triggered by input to trigger point (pin 2).

Circuit modifications

- For linear ramp generation, constant-current charging is required. Matched transistors (as in RCA CA3084) form current mirror in which collector current of Tr_3 (left) is set by current in Tr_1, with only small influence of collector-emitter p.d. Any alternative current generator with p.d. < $\frac{1}{3}V$ may be used such as that on card 2.
- Capacitor cannot be loaded resistively without disturbance to waveform. Operational amplifier used as voltage follower, or f.e.t. as source follower, are suitable buffers for this (middle diagrams), and corresponding portions of cards 3, 4 & 6 may benefit from the same technique.
- For minimum flyback time the discharge current must be increased. If the flyback time is negligible compared to ramp time, then linear voltage control of the latter gives linear control of frequency. Diagram right shows the main output returned through D_1 to the capacitor i.e. using output current capability to reduce flyback time. Fall-time of < 1μs for C = 0.1μF is possible at V = +10V.

Cross references

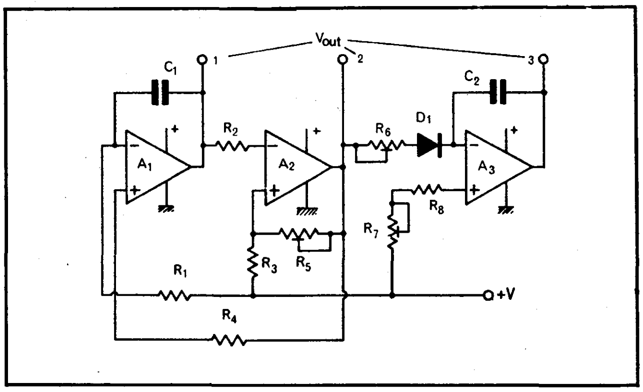
Series 3 cards 2, 4 & 6.


Circuit modifications

Wireless World Circard

Series 3: Waveform generators 10

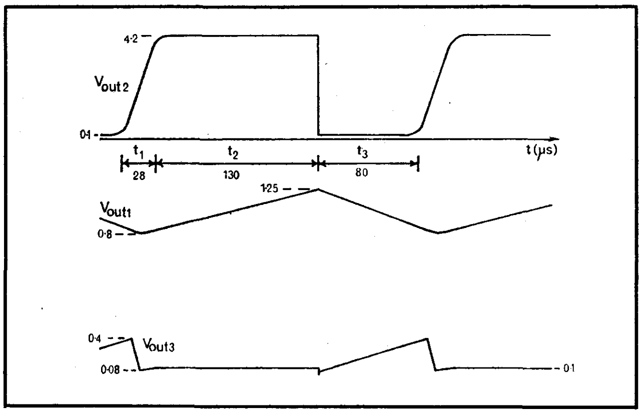
Simple multi-waveform generator



Typical performance

Supply: +5V
A_1-A_3: LM3900
R_1: 1MΩ; R_2: 100kΩ
R_3: 1.2mΩ; R_4: 470kΩ
R_5, R_6, R_7: 1MΩ pot.
R_8: 22kΩ; C_1; C_2: 1nF

D_1: PS101
With R_5, R_7 = 1MΩ & $R_6 = 0$ output waveforms are typically as shown right.



Circuit description

Operational amplifiers whose output depends on the difference between two input currents can be used as novel waveform generators. Thus A_1 integrates the difference in current in R_1 and R_4. The former is constant and the latter switches between some positive value and substantially zero (the potentials at the inputs of all these amplifiers are about + 0.6V w.r.t. the common line, using a single-ended positive supply). If the on-current in R_4 is double that sustained in R_1, the difference then changes polarity with equal magnitude for the two polarities. The output of A_1 is a linear ramp that at some potential provides a current in the inverting input of A_2 that initiates a switching action, reverses the output of A_2 and causes the integration to proceed with opposite slope. Resistor R_5 controls hysteresis on A_2, amplitude of the triangular wave and also frequency. Control of frequency with a single resistor is more difficult than for circuits using conventional op-amp circuits as the ratio R_1/R_2 has to be maintained for symmetrical triangular waves. The output is fed to a second integrator A_3 but at an amplitude sufficient to ensure eventual saturation. Slopes of the edges can be varied by R_6 and R_7.

Component changes

Maximum useful frequency ≈ 20kHz.
Useful C_1 range ≈ 10pF to 22μF.
R_5 min ≈ 100kΩ (V_{out_1} switches to +4.2V).
With R_5 = 105kΩ, V_{out_1} = 3.7V pk-pk, V_{out_3} = 3.3V pk-pk, t_1 = 28μs, t_2 = 1.26ms, t_3 = 800μs.
R_6 max ≈ 770kΩ (V_{out_3} becomes: +4.3V d.c.).
With R_5 = 105kΩ, R_6 ≈ 490kΩ: V_{out_3} is triangular;
R_6 > 490kΩ, V_{out_3} is a trapezium clamped at 4.3V;
R_6 = 0, R_7 = 433kΩ to 1MΩ, V_{out_3} is a ramp;
R_6 = 0, R_7 = 11 to 433kΩ, V_{out_3} is a trapezium;
R_6 = 0, R_7 = 5kΩ, V_{out_3} is a square wave (anti-phase with V_{out_2}) and may be made a trapezium or a ramp waveform by selecting C_2 between 10pF and 100nF.

Circuit modifications

- Remaining amplifier in the LM3900 package may be used as an inverter (see left) fed from any one of the existing outputs to provide a pair of antiphase triangular, square, ramp or trapeziodal outputs.
- This amplifier may also be used as a summer for two or more, of the existing outputs (middle) to produce more complex waveshapes.
- If dual polarity supplies are used then R_x above should be reduced to 1MΩ and connected to 0V instead of the +V rail.
- For certain values of R_6 and R_7, V_{out_3} will not be clamped to either a low or a high level. To remove this indefinite state, d.c. feedback can be added to A3 as shown right.

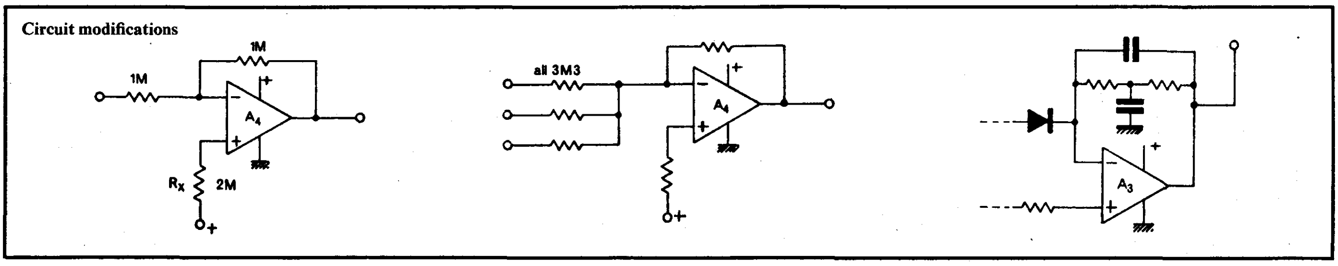
Further reading

LM3900 Quad Amplifier, data sheet and application note, National Semiconductor, 1972.
Gledhill, B., Analogue module applications, *Electronic Engineering*, March 1970, pp.64/5.

Cross reference

Series 3, card 11.

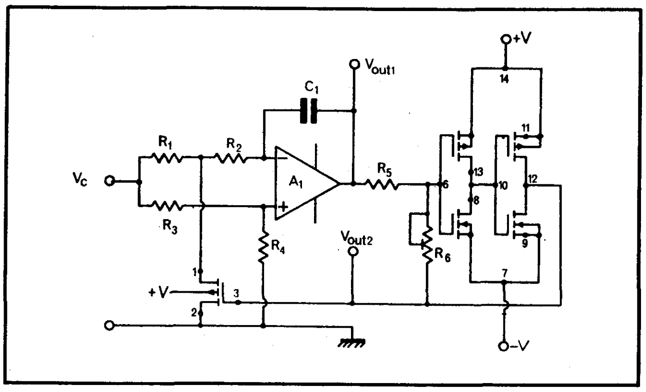
Circuit modifications



Wireless World Circard

Series 3: Waveform generators 11

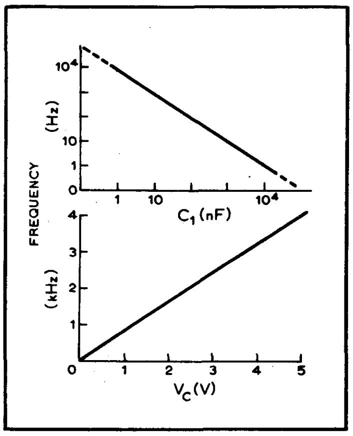
Op-amp/c.m.o.s. square/triangle generator



Typical performance

Supplies: +5V
A_1: 741
c.m.o.s. inverters: $\frac{1}{3}$ × CD4007AE
c.m.o.s. switch: $\frac{1}{6}$ × CD4007AE
(R_1 + R_2); (R_3 + R_4): 47kΩ
R_5: 100kΩ, R_6: 1MΩ pot.
C_1: 1nF

Variation of frequency as function of C_1 (V_C = + 1V) and of V_C (C_1 = 1nF) shown right, with $R_1 = 2R_2$, $R_3 = 2R_4$ and R_6 = 1MΩ.
At 10kHz, V_{out_1} is symmetrical triangular wave of 1.3V pk-pk and V_{out_2} is 1:1 square wave, 10V pk-pk.



Circuit description

One limitation to the basic triangle-square generator is that the output amplitude of the Schmitt depends on the saturation limits of the amplifier/comparator used–the hysteresis and hence triangular wave amplitude and frequency are device-temperature variable. The circuit shown uses a c.m.o.s. Schmitt whose output swings almost exactly to the supply limits provided it is lightly loaded. Such a circuit can be provided by a single c.m.o.s. package while leaving at least one m.o.s. device free to act as a switch driven by the Schmitt output. The switch may be used to invert the current flow within the integrator, or to invert the gain of a preceding amplifier where the circuit is to be used as a voltage-controlled oscillator.

The circuit makes very economical use of the lowest-cost c.m.o.s. package to provide triangular and square waves whose amplitudes are constant for constant supply voltage. A further advantage is that the Schmitt current is negligible except at the switching point. The main disadvantage is that the c.m.o.s. threshold voltage, while close to $V/2$, has some tolerance and the triangular wave will have a non-zero mean potential.

Component changes

Maximum useful frequency: 50kHz (C_1 = 1nf; V_C = +1V)
R_6 min ≈ 60 kΩ (loss of triangular wave).
Increasing R_1/R_2 increases +ve slope of V_{out_1}, without changing its -ve slope, increases V_{out}, and increases mark-space ratio of V_{out_2} (22:1 when R_2 zero).
Decreasing R_1/R_2 reduces +ve slopes of V_{out_1} without affecting its -ve slope, reduced frequency (f_{min} ≈ 600Hz), and reduces mark-space ratio of V_{out_2} (1:32 min at f ≈ 700Hz).
Increasing R_3/R_4 reduces +ve and increases -ve slopes of V_{out_1}, reduces frequency (f_{min} ≈ 300Hz), and reduces mark-space ratio of V_{out_2} (1:60 min at f ≈ 400Hz).
Reducing R_3/R_4 increases +ve and decreases -ve slopes of V_{out_1}, reduces frequency (f_{min} ≈ 20Hz), and increases mark-space ratio of V_{out_2} (500: 1 max. at f ≈ 100 Hz).

Circuit modifications

- Variable voltage control input (V_C) may be derived from a potentiometer (R_7 ≈ 5kΩ, left) connected between +V and 0V rails, which provides first-order compensation for supply voltage changes.
- Useful frequency range of the circuit may be extended to about 250kHz by using a fast integrator. Middle diagram shows an example where A_1 is an LM301A, C_2 10pF, C_3 150pF and R_8 5kΩ.
- In place of a c.m.o.s. device, the switch may be realized by a discrete transistor e.g. BC125. Inclusion of R_9, typically 10kΩ, as shown right allows the triangular output to swing symmetrically with respect to 0V.
- A third output is available at pin 10 of the CD4007AE which provides a square wave in push-pull with V_{out_2}.

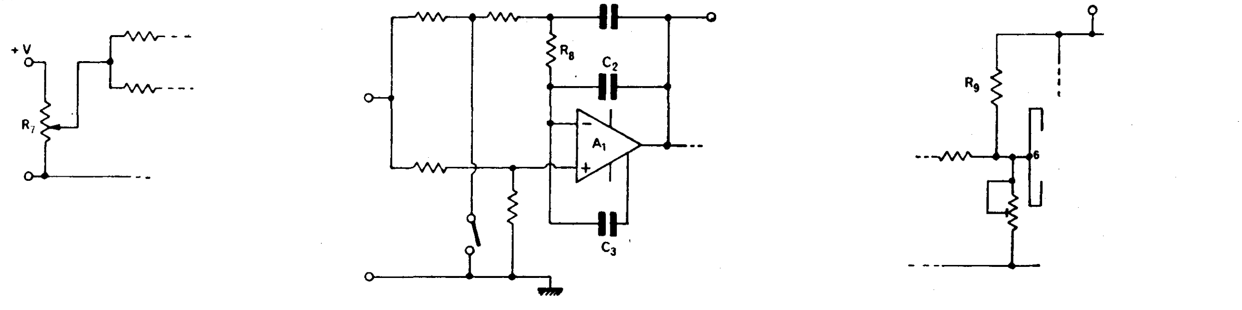
Further reading

Simple square-triangle waveform generator, *Electronic Engineering*, Oct 1972, p.29.
Smith, J. I., Modern Operational Circuit Design, 1971, p.224/5.

Cross references

Series 3 cards 1, 2, 5, 7 & 10.

Circuit modifications



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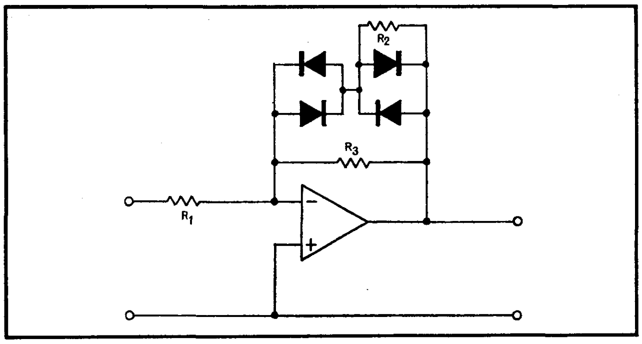
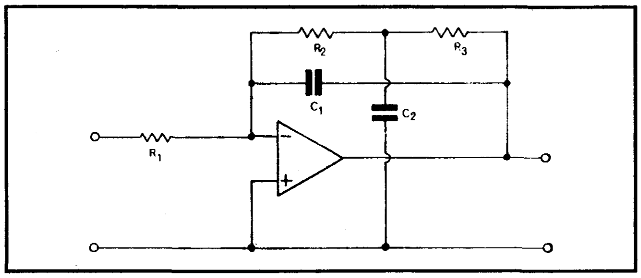
Simple wave-shaping circuits



f: 1kHz
R_1: 22kΩ±5%
R_2: 100kΩ±5%
R_3: 27kΩ±5%
Diodes 1N914

Adjust input triangular wave amplitude for minimum output distortion (~ 2V pk-pk) Distortion < -43dB using distortion factor meter. Visual adjustment possible to -35dB to 40dB.

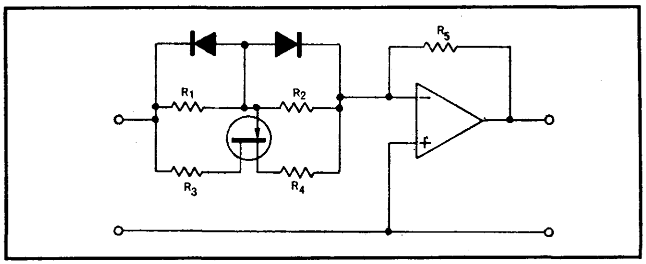
If a repetitive waveform is fed to an amplifier with a non-linear transfer function, the output waveform differs from that of the input. In the circuit shown the diodes across the feedback resistors are non-conducting for small signals and the output waveform is an inverted version of the input. As the amplitude increases, the diodes are progressively brought into conduction and the output increases more slowly than the input. With the values shown an input triangular wave produces a sinusoidal output with total harmonic distortion <1% on two conditions: that the input contains no significant d.c. component, and that the input resistor is adjusted for the particular value of input voltage. Component values were determined empirically with the diode non-linearities smoothing the transitions between the defined regions of the transistor function.



f: 1kHz
R_1: 15kΩ±5%
R_2: 100kΩ±5%
R_3: 100kΩ±5%
C_2: 1μF±10%
C_1: 10nF±10%

Output $\propto (1/fR_1C_1)$
Output amplitude ≈ input amplitude for above typical values and sinusoidal/triangular wave inputs.

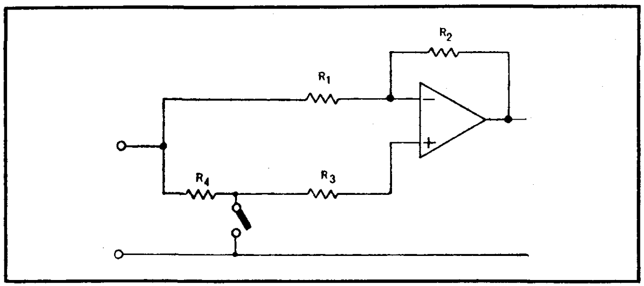
A third method of generating an approximate sine wave which is not strictly wave-shaping in the above sense is to apply a triangular wave to an integrator with overall decoupled d.c. negative feedback to define the mean output voltage. The integral of a linear ramp is parabolic in form, and the combination of two successive parabolas corresponding to the positive and negative slopes of the triangular waves gives a crude approximation to a sine wave with harmonic distortion of about 4%. The one advantage of this circuit over the previous is that the wave shape is independent of input amplitude, but the output amplitude is inverse to frequency.



f: 1kHz
R_1: 1MΩ±5%
R_2: 1MΩ±5%
R_3: 470Ω } matched
R_4: 470Ω } to ±2%
Diodes 1N914

Adjust input triangular wave amplitude as for 1. Distortion <-40dB. Select R_5 for desired output, typically 1 to 10kΩ.

Placing a non-linear element in the input path also modifies the output, and to convert a triangular wave into an approximate sinusoidal wave an f.e.t. may be used. The source and drain are interchangeable and the diodes ensure that for either polarity of input the f.e.t. is effectively operated with low V_{gs}. At low input voltages, the f.e.t. has a low and relatively constant slope resistance, rising progressively as the input brings it towards pinch-off. If the input voltage has $V \approx V_p$ for the f.e.t., the output peak is just flattened and distortion of less than <1% is again possible. The gate bias resistors should be large and the source and drain resistors equal. If the f.e.t. or diode networks are reversed, so is their action–the magnitude of the transfer function increases as the input amplitude rises. Any other devices with controlled non-linearities may replace the above.



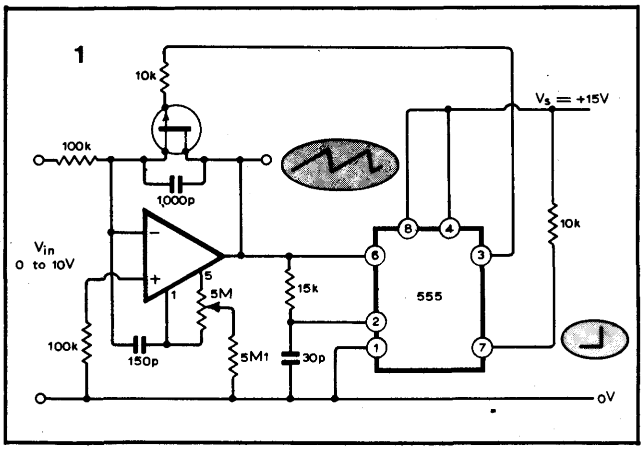
Using an ideal switch and $R_1 = R_3$, gain is exactly inverted. Switch may be driven by the squarewave of a square/triangle generator, and the circuit then inverts alternate ramps to give saw-tooth.
R_1 to R_4: 100kΩ.

An alternative to controlled non-linearity is to introduce an instantaneous change in gain at some precise point in a waveform. This can be conveniently done if a square wave is available simultaneously with the waveform to be modified, as in the triangle/square generators described earlier. If the triangular waveform is passed through an amplifier whose gain is inverted at each peak of the triangular wave, the result is a sawtooth wave at twice the frequency. The switching of the amplifier gain may be carried out using f.e.t. switches as described in previous cards. A further modification involves the superposition of a portion of the square wave on the sawtooth, producing a sawtooth at the original frequency but with a transient at the ramp mid-point.

Cross reference
Series 3, card 7.

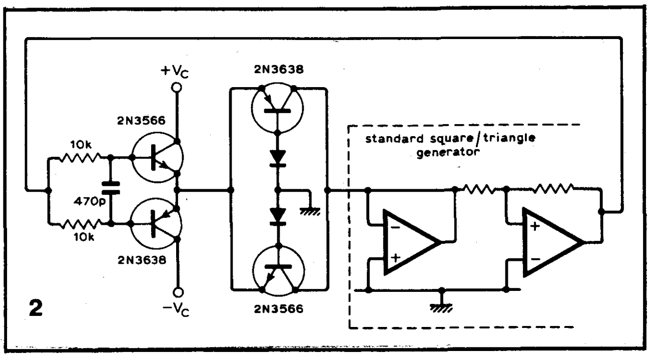
Waveform generators

1. Ramp/triangle generators can be constructed using an integrator and a level-sensing circuit to determine the end-points of the waveform. The 555 timer is ideal for such applications since it has internal comparators that provide sharp switching at well defined levels of $\frac{1}{3}$ and $\frac{2}{3}$ of the supply voltage. The main output can be used to switch an f.e.t. that discharges the integrator capacitor when the integrator output reaches $\frac{2}{3}V_s$. The second output of the timer is an open-collector device that can have t.t.l.-compatible swings if its load resistor is returned to +5V. The circuit has good linearity up to 10kHz with a conversion ratio of 1kHz/V.



2. A means is shown to increase the frequency range of a standard square/triangle function generator by applying control voltages to the emitters of a pair of matched complementary transistors. The resulting current flow is a good approximation to an exponential function of the control voltages ±Vc, which can be provided by a single control voltage and an amplifier of voltage gain −1. The transistors switching the control voltages arealternately saturated by the drive resistors. The frequency is an exponential function of the control voltage making it useful for plotting the frequency characteristics of other circuits.

Hiscocks, P. D. Function generator mod. for wide sweep range, *Wireless World*, vol. 79, 1973, p.374.



3. The conventional astable multivibrator has an approximate ramp waveform at the base of each transistor only if the base return voltage is greatly in excess of the collector supply. Alternatively if the ramp amplitude is restricted better linearity results. Diode feedback across each transistor collector-base clamps the negative base swing to ≈ −0.4V. The base forward voltage is ≈ +0.6V giving a 1-V ramp much less than the supply voltage. If the collector ramps are summed in a diode OR gate, a sawtooth waveform results. The amplitude is reasonably constant against supply changes, but since the collector resistors also provide the return paths for the capacitors the frequency is to a first order proportional to the supply voltage – i.e. a simple v.c.o.

Hari, S. Minor changes convert an astable multivibrator into a sweep generator, *Electronic Design*, vol. 21, 1973, p.72.