Wireless World Circard Series 3: Waveform Generators-1

Basic op-amp square/triangle generator

Circuit description
When a positive voltage is applied to the input of the inverting integrator, consisting of R2, R3, C and IC1, 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 signal is much less than the constant current in IC1, the output voltage rises linearly with time. As the value of 1/Cthe negative current fed back through R2 will overcome the positive current in R3 and R4, and the resulting negative current in the non-inverting input of IC1 initiates a negative going transition in V2. 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 V2 back to its original positive value.

Data
IC1, IC2: 741
Supplies: ± 6 to ± 15V
I2: ± 0.9V
V1: 1 to 20V pk-pk
Frequency: zero to 3kHz
R1: 10kΩ; R2: 8.2kΩ
R3: 1MΩ; R4: 220kΩ
R5: 1.2kΩ; C: 0.1μF

Hence V3 is a square wave and V1 a triangular wave. Resistor R4 gives independent frequency control and R5 varies the frequency and the magnitude of V1.

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 IC1. A 301 op-amp will permit frequencies of up to 10kHz to be achieved, the square wave degenerating visibly before the triangular.
- R1 and R3 limit the current drawn from IC1, when R4 and R5 are in their minimum positions and could possibly be omitted.
- R2 may be varied widely but must not be so low that IC1 is heavily loaded and not so high that IC1 does not switch before IC2 reaches saturation.
- C can also be changed, bearing in mind that the slope of the triangle is inversely proportional to (R1 + R3).

Wireless World Circard Series 3: Waveform Generators-2

Emitter-coupled triangular wave generator

Circuit description
The circuit is an emitter-coupled astable circuit normally fed from a voltage source. This results in sharp transitions in the voltages across R3 and R4 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 Tr1 fully conducting, Tr2 off. The charging circuit is then as shown in the above diagram. Provided the conditions v < v3, and v1 = v2 are maintained, the capacitor charges linearly, but in any case for R3 = R4, any rise in v1 must be accompanied by an identical fall in v2, to maintain a constant total current. Hence there are two outputs v3 and v4 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 ≥ -0.5V at which condition Tr2 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 R4 determines the value of I.

Component changes
Useful range of C: 1μF to 3.6 nF
Frequency range: 0.5 to 130kHz
A 20% reduction in VCC varies frequency by about 5%.

Typical performance
Tr1, Tr3: BC125
Tr2: BC126
VCC: ±15V
C: 0.1μF
R3: 2.2kΩ
R4: 330Ω
R5: 4.7kΩ
R6: 10kΩ
f: 5.3kHz
f/ ≈ 1/C

v1 = v2: Antiphase triangular waveforms
0.4V pk-pk on a d.c. level of 4V. As R3 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 modifications

- The triangular wave can be given a d.c. offset of either polarity by applying a bias signal $V_b$, as shown left in which $R_b = 10k\Omega$. The bias can be increased to the point at which the integrator saturates without changing the state of IC.

- A sawtooth waveform can be achieved by adding a d.c. signal $V_b$ to the integrator output, as shown middle. The magnitude of $V_b/R_b$ must be less than $[V_b/(R_1 + R_2)]$ otherwise the integrator output will not change direction as $V_b$ changes sign. Time $t_1$ is greater than $t_2$ if $V_b$ is positive and $t_1$ is less than $t_2$ if $V_b$ is negative. The ratio $V_b/R_b$ must be comparable to $V_b/(R_1 + R_2)$ if a large mark-space ratio is required. Independent frequency control through $R_2$ 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 $R_2 + R_4$ and on the positive-going side by $R_3$ in parallel with $R_1 + R_4$.

- The output of IC1 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 ICs is possible at low signal levels by means of terminals on the IC (cross ref. 2).

Further reading


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

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Diode-pump staircase generator

Circuit description
The basic diode pump has diode D; feeding capacitor C2 (grounded) and without the amplifier. On the first positive input pulse D; conducts and provided the pulse duration is long enough the pulse amplitude is shared between C1 and C2; the same charge producing the larger portion of the p.d. across the smaller capacitance. On each succeeding pulse the previously established across C2 opposes any fresh flow of charge, and the step in the output voltage diminishes progressively to zero when the p.d. across C1 equals the input pulse amplitude. In the circuit shown the amplifier virtual earth prevents the p.d. across C2 from influencing the charge flow on successive cycles and the p.d. builds up in equal steps. In each case the charge acquired by C1 during the pulse is lost to ground through D2 when the input returns to zero i.e. C1 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 C2; to make the circuit free-running a device such as a unijunction transistor must be added to provide periodic discharge of C2 and such devices contribute additional leakage currents.

Component changes
C1: 1000pF to 1nF
C2: 100pF to 1nF
D1, D2: general-purpose Si diodes
IC: any general-purpose compensated op-amp e.g. 307.
Vin: 1 to 20V pk

Unijunction sawtooth generator

Circuit description
Circuit is used as a sawtooth (V2) or a trigger pulse generator (V1). Capacitor C charges through R2 until the unijunction transistor Vf is reached and then discharges via R1 until the transistor changes made at approximately 0.5Vf (sat.); C then starts charging through R2 again. Waveform frequency \( \approx \frac{1}{R2C} \). With R2 fixed at 10k\( \Omega \) and C varied, the waveform details (apart from the period) remain identical as C is reduced down to 220 nF. At 10nF, V1 is reduced to half its previous value and the pulse width increases approximately 1/10th of the period. At 1nF the pulse height is further reduced and V2 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 B1. 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 V1 to become zero but has little effect on V2. 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.
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 10kHz.

Circuit modifications
- Use of bootstrap technique returns r.h. end of C1 to output through D3 at end of each positive pulse. This ensures that on next positive pulse D1 begins to conduct at start of pulse even if p.d. across C2 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.
- An alternative range of transistor-pump circuits may be devised. On the positive edge, D3 conducts and C1 and C2 charge with p.d. shared between them in inverse ratio to capacitance. On negative edge, Tr. conducts clamping C1 to just below output while discharging C2 only by base current of Tr

Circuit modifications
- Discharge time through R1 may be greatly reduced by the modification, shown left, in which V2 is used to short the capacitor to ground. This makes the pulses of V1 much narrower. makes V3 almost ramp like and also alters the frequency slightly.
- The unijunction transistor may be replaced by the two transistor version, shown middle, with R1 100Ω, Tr1 BC126, Tra BC125 and the potentiometer 2.2kΩ. The lower value of V1 in this case comes much closer to zero. The potentiometer is set to the maximum value of V3 required plus 50V.
- 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 V1 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, connecting the capacitor directly to the supply, provided the capacitor voltage is less than the eventual minimum value of V1 (ref. 2).

Further reading

Cross references
Series 3, cards 4 & 5.

Further reading

Cross references
Series 3, cards 2 & 8.
Wireless World Circard Series 3: Waveform Generators-5

**Voltage-controlled square/triangle generator**

![Circuit diagram](image)

**Typical performance**
- IC1: 741
- IC2: 301
- IC3: 1 (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 IC3 controls on electronic switch $Q_1$ (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 IC1 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 $V_{CC}$. 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 series or series-parallel switch that can make the potential of the inverting input resistor alternate between ground and $V_{CC}$.

Wireless World Circard Series 3: Waveform Generators-6

**Complementary transistor sawtooth generator**

![Circuit diagram](image)

**Typical performance**
- $V_{CC}$: +15V
- $T_1$: BC125, $T_2$: BC126
- $R_1$: 2.2kΩ, $R_2$: 22kΩ
- $R_3$: 15kΩ, $R_4$: 1MΩ (pot)
- $C$: 10µF
- $V_{out}$ oscillates from 2.8V 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 $T_1$ is zero and no current flows in either $T_1$ or $T_2$. The p.d. across $R_1$ 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 $R_1$ falls and with it the rate of charge. When the potential at the base of $T_1$ exceeds that at the base of $T_2$ by ~ 1V the transistors begin to conduct. This reduces the potential at $T_2$ collector and at the base of $T_2$ 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 $T_1$). Similarly the potential at $T_2$ collector falls. After the switching transient, the charging 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, $R_{min}$ ≈ 47kΩ, $R_{max}$ ≈ 2.6 MΩ. Useful range of $C$: 47pF to 32µF (tantalum bead). Maximum useful frequency ≈ 70kHz.

Changing the ratio $R_1$, $R_2$ alters the voltage to which $C$ charges.
Component changes

- Frequency is linearly related to control voltage $V_C$ up to 4V.
- Useful range of $C$: 100 pF to 0.1 nF.
- Positive feedback via $R_1$ must be at least 75% to maintain triangular shape, because of saturation of the IC, 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, $C = \ln F_{V_C} = 4V$, mark space can be 1:15 at $f = 1250Hz$ to 1:1 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 'shift 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 $C = \ln F$, $n = 1$.

Further reading


Cross references

Series 3, card 11.

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Circuit modifications

- A resistor may be included in $T_2$ collector ($R_3$ in Fig on left) to provide a train of narrow pulses typically of amplitude 0.6V when $R_3 = 100k$. Anti-phase pulses, of amplitude $\pm 0.4V$ are available at $T_3$ collector.
- Resistor $R$ may be returned to the $V_{CC}$ rail instead of $T_3$ collector, as shown middle. To increase $R$ above 2.6MΩ, current gain of $T_3$ could be increased by replacing it with a Darlington unit.
- Speed-up capacitor $C_2$ 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.

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Further reading


Cross references

Series 2 card 12.
Series 3 card 9.
**D/A converter waveform generator**

**Typical performance**
- IC: CD4024A
- Supply: +5V
- \( R_1 = 90k\Omega \)
- \( R_2 = 47k\Omega \)
- \( f_m = 12.58\, \text{Hz} \)
- \( f_{out} = 100Hz \) i.e. for waveform shown, \( T \) is 10ms.
- For a 7-bit counter, waveform comprises 128 steps.
- Minimum input level: 1V
- Maximum input pulse: 3.5V

**Circuit description**
If the output of a binary counter is used via buffer stages to drive a resistance 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 waveform 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 analog 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.

**Triggered ramp/trapezium generator**

**Typical performance**
- Supply (V): +10V
- IC: LM335
- \( R_1 = 220k\Omega \)
- \( R_2 = R_3 = 100k\Omega \)
- \( C_1 = 47\mu F \)
- \( C_2 = 100nF \)
- \( C_3 = 22\mu F \)
- \( D = \text{SD2} \)
- With transistor version (over, left), where \( Tr_1 \) is BFR41, \( R_1 = 1k\Omega \), \( R_2 = 47\Omega \).
- \( f_{peak} = 1V \)
- Period is 66ms, width is 30ms, and source res. 500Ω, waveforms are typically as shown right.

**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.e., voltage regulator having internal current limiting. At switch on, capacitor \( C_2 \) 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 \( R_1 \) 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 \( R_2/R_1 \). 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.d.s, 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 \( Tr_1 \) driver from a pulse source is one example.
Component changes
Maximum useful output frequency: 1kHz, demanding an input p.r.f. of 12kHz. 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 left. Resistor R1 is 33kΩ, IC1 = 1 (CD4016) c.m.o.s. transmission gate. Resistors R4 and R5 are 100kΩ. R2: 84kΩ and R3: 16kΩ.
Diagram on right 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 R6 is 750kΩ for the above values of R4, R5.

Further reading

Cross references
Series 3, cards 3, 11 & 12.

Component changes
Maximum useful frequency ≈ 100kHz.
With R1 equal to 100kΩ, variation of R2 over the useful range 22 to 150kΩ varies Vout between 8.5 and 3V. Output voltage waveform becomes a ramp either when R1 is increased to about 4700 or C1 increased to about 32µF.
With C1 equal to 22µF, max. useful R2 is about 10kΩ (ramp amplitude no longer defined by regulator feedback resistors R2 and R3).
With R1 equal to 1kΩ, max. useful C1 value is about 3000µF.
With R1 set at 2200, Vout becomes a square wave with C1 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 R6: 330Ω, C1: 1000µF & R5: 1000Ω.

Circuit modifications
To give a higher output current rating and to provide a foldback (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: Vc: +10V, R1: 5Ω, R2: 3.9kΩ, R3: 1kΩ, R4: 15Ω
R5 + R4: 1kΩ, C1: 47µF, C2: 100nF, C3: 4000µF, Tr1: BFR41, Tr2: BFR81, Vc: +3.6V. Period: 45ms, pulse width: 26ms, pulse source resistance: 500Ω.
With R6 + R6 equal to 1kΩ, R6 should not be greater than about 200Ω to obviate excessive instability of the regulator due to the negative resistance characteristic. Lower level of Vout is less well-defined than its upper level due to dependence on VCE (sat) of Tr1 and VD amplitude.

Further reading

Cross reference
Series 3, card 4.
Stable waveform generator using single i.c.

Typical performance
IC: NE555 (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_B/C
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 waveform shape can be modified by changing the charge/discharge circuit C. Under the flip-flop in the state that leaves Tr, non-conducting. The capacitor charges through R_A + R_B until the high-level comparator reverses the flip-flop. Transistor Tr 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 < R_A the flyback time is very short, and sawtooth waveforms are possible. Conversely for R_B > 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 1/3 and 2/3.
Unless the load resistance is > R_A and R_B, buffering of the output from the capacitor is required. A short 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.

Wireless World Circard Series 3: Waveform Generators–10

Simple multi-waveform generator

Typical performance
Supply: +5V
A1-A3: LM3900
R1: 1MΩ; R2: 100kΩ
R3: 12mΩ; R4: 470kΩ
R5, R6, R7: 1MΩ pot.
R7: 22kΩ; C1, C2: 1nF
D1: PS101
With R, R: 1MΩ & R. 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 A2 integrates the difference in current in R1 and R4. 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 R4 is double that sustained in R1, the difference then changes polarity with equal magnitude for the two polarities. The output of A3 is a linear ramp that at some potential provides a current in the inverting input of A2 that initiates a switching action, reverses the output of A3 and causes the integration to proceed with opposite slope. Resistor R1 controls hysteresis on A3, 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 R1/R2 has to be maintained for symmetrical triangular waves. The output is fed to a second integrator A3 but at an amplitude sufficient to ensure eventual saturation. Slopes of the edges can be varied by R6 and R7.
Component changes

- **Vₐ**: +4.5 to +16V
- **Rₓ**: 1kΩ to 1MΩ
- **Rᵧ**: 1kΩ to 1MΩ
- **C**: 100 pF to 1000 pF

- Control voltage (pin 5) varies on and off levels in some ratio, allows modulation of frequency, but also changes amplitude of capacitor waveform.
- Addition of silicon diode in parallel with Rᵧ, conducting on forward stroke makes charge time dependent on Rᵧ. Discharge still depends on R₀, i.e. Duty cycle adjustable ≥ 50%. Diode drop affects accuracy, particularly for low Iᵣ.
- 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 Trᵣ (left) is set by current in Trᵣ, with only small influence of collector-emitter p.d. Any alternative current generator with p.d. < 1V 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 Dᵣ to the capacitor i.e. using output current capability to reduce flyback time. Fall-time of ≤ 1µs for C = 0.1µF is possible at Vᵣ = 10V.

**Further reading**

Application report: 555 timer, Signetics.

**Cross references**

Series 3 cards 2, 4 & 6.

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Wireless World Circuit Series 3: Waveform Generators-11

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

Typical performance
Supplies: +5V
A1: 741
C.m.o.s. inverters: \( \times 1 \times \)
CD4007AE
C.m.o.s. switch: \( \times \)
CD4007AE
\( R_1 + R_2 \): \( R_1 + R_2 \) 47kΩ
\( R_4 \): 100kΩ, \( R_3 \): 1MΩ pot.
\( C_1 \): 1nF

Variation of frequency as function of \( C_1 \) (1F, +1V) and of \( V_{in} \) (C1, 1nF) shown right, with \( R_1 \): 2R, \( R_2 \): 2R, and \( R_3 \): 1MΩ.
At 10kHz, \( V_{out} \) is symmetrical triangular wave of 1.3V pk-pk and \( V_{out} \) 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 feedback 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.

Wireless World Circuit Series 3: Waveform Generators-12

Simple wave-shaping circuits

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.

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 separated with low \( V_g \). 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 \( V < V_g \) 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.
Component changes

Maximum useful frequency: 50kHz (C₁ = 1nF; V_C = +1V)
R₂ min = 60 kΩ (loss of triangular wave).
Increasing R₁/R₂ increases the slope of V_out, without affecting its -ve slope. Reduced frequency (f_min ≈ 600Hz), and reduces mark-space ratio of V_out, (1.32 min at f ≈ 700Hz).
Increasing R₁/R₂ reduces -ve and increases +ve slopes of V_out, reduces frequency (f_min ≈ 300Hz), and reduces mark-space ratio of V_out, (1.60 min at f ≈ 400Hz).
Reducing R₁/R₂ increases +ve and decreases -ve slopes of V_out, reduces frequency (f_min ≈ 20Hz), and increases mark-space ratio of V_out, (50:1 max. at f ≈ 100 Hz).

Circuit modifications

- Variable voltage control input (V_C) may be derived from a potentiometer (R₁ = 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 25kHz by using a fast integrator. Middle diagram shows an example where A₁ is an LM301A, C₂ 10pF, C₃ 150pF and R₃ 5kΩ.
- In place of a c.m.o.s. device, the switch may be realized by a discrete transistor e.g. BC125. Inclusion of R₅, 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 CD4007A which provides a square wave in push-pull with V_out.

Further reading


Cross references

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

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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%. One advantage of this circuit over the previous is that the wave shape is frequency independent, though the amplitude is inversely to frequency.

Using an ideal switch and R₁ = R₂, 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.
R₁ to R₂: 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 i.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.

Further reading


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