Build Your Own Sweeping Function Generator
by Dennis L Feucht

In the mid-1970s, I was designing test and measurement (T&M) instruments in the TM500 group at Tektronix. One instrument I designed never made it to market, not because of technical problems but because of marketing overlap with another product (the FG504). The tentatively-named FG506 did not make it out of product development, though fully working prototypes meeting specs were built in engineering. A photo of a prototype FG506 is shown below.

This project is based on the FG506, with possible updates to the mid-'70s design. As it stands, it is still a viable design in that it is maintainable; it is field repairable, and has no unobtainable custom parts other than the front-panel knobs. Those can be substituted, or even eliminated, in a µC-based version, and ordinary knobs will do in the existing "hot-switched" version. To also provide some insight into product development at a leading electronics company, I will include some of the engineering considerations during the project.

FG506 Features

One of the early steps in the development of a new product is to provide management a product description of what is proposed. This description includes proposed price, the production cost target, specifications, and features. The price and performance of the proposed product is compared to other products, both those of the company and from competitors. I wrote what I thought was a rather complete list of FG features as a warm-up exercise for selecting which features the FG506 should have, as follows:

I. Amplitude Modulation (AM)
   1. External
   2. Internal
      a. triangle
      b. sine
      c. square
      d. sine-squared

II. Frequency Modulation (FM)
   1. External VCF (voltage-controlled frequency)
   2. Phase locking
   3. Internal VCF
      a. linear sweep
      b. stepped sweep
      c. "log" (exp) sweep
      d. calibrated sweep limits

III. Gating
   1. direct
   2. triggered
   3. variable phase
   4. single cycle
   5. selected N cycle

IV. Variable Symmetry
   1. fixed symmetry offset (ramps, pulses)
   2. variable symmetry (duty ratio)
   3. pulse-width modulation (PWM) or VCS (voltage-controlled symmetry)

V. Output
   1. multi-phase outputs
   2. multi-function outputs
   3. trigger out
   4. sweep duration out
   5. output blanking during sweep retrace
   6. offset control
   7. calibrated attenuator
   8. internal VCF sweep function out
   9. variable rise and fall times
   10. phase-locked phase detector out

FG506 Specifications

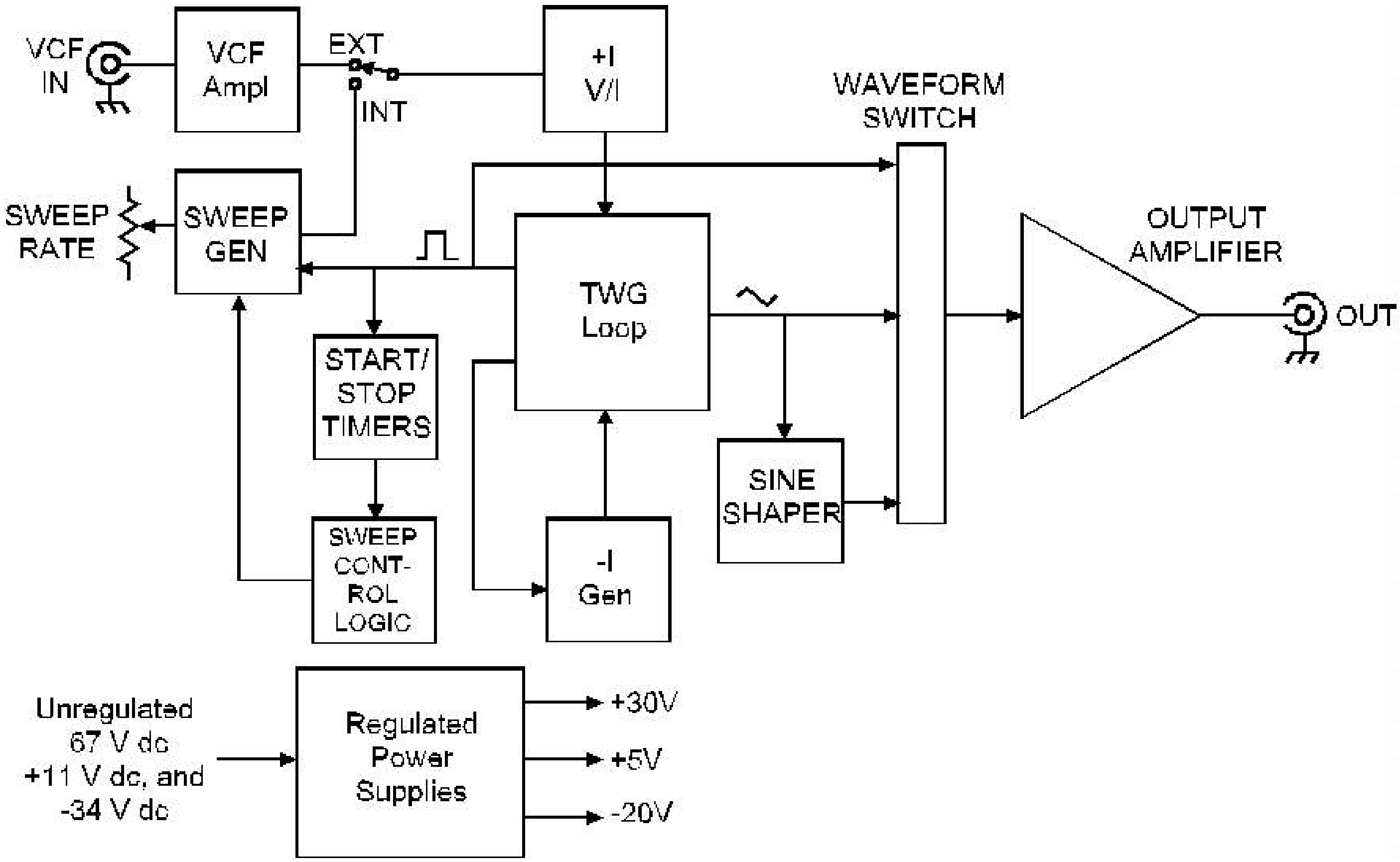
From this list, features were chosen for the FG506, resulting in the following specifications:

Outputs: sine, triangle, square waveforms; sweep gate pulse during sweeping (for recorder gating): high logic level ⇒ up (increasing frequency) sweep
Frequency Range: 10 Hz to 100 kHz in 4 decade steps
Output Amplitude: 20 Vpk-pk open circuit; 10 Vpk-pk into 50 Ω, variable; minimum amplitude ≤0.5 V into 50 Ω
Dial Accuracy: (start and stop frequency dials) ≤5% of FS (full-scale) of start frequency dial [This could be significantly improved in a μC-based FG506].
Amplitude flatness: ≤0.1 dB
Sine-wave Distortion: ≤0.5% THD, 10 Hz - 100 kHz; < 0.3% typical
Triangle Symmetry: ≤1%
Triangle Linearity: ≤1%
Square-wave: risetime ≤100 ns; aberrations ≤3% pk-pk, full amplitude
Sweep Gate Out: +2.5 V TTL out from 220 Ω
Internal VCF In: 0 V to 10 V ⇒ 10 Hz to 100 kHz, linear
Internal Frequency Sweep: logarithmic
Operating Modes: HOLD at start frequency, HOLD at stop frequency; SWEEP between start and stop frequencies
Output Blanking: output = 0 V during down sweep
Sweep Range: max range from 10 Hz to 100 kHz; both sweep end limits selectable between 10 Hz to 100 kHz

The specifications of a product will also include the environmental conditions for operation (0°C - 50°C, with instrument calibrated at 25°C) and give a warm-up time (20 minutes) for the specifications to be valid. Other specifications such as humidity might also be added. For the FG506, the assumption is that it will be used on an electronics test bench in an environment suitable for electronics.

Block Diagram

The system-level diagram for the FG506 is shown below.

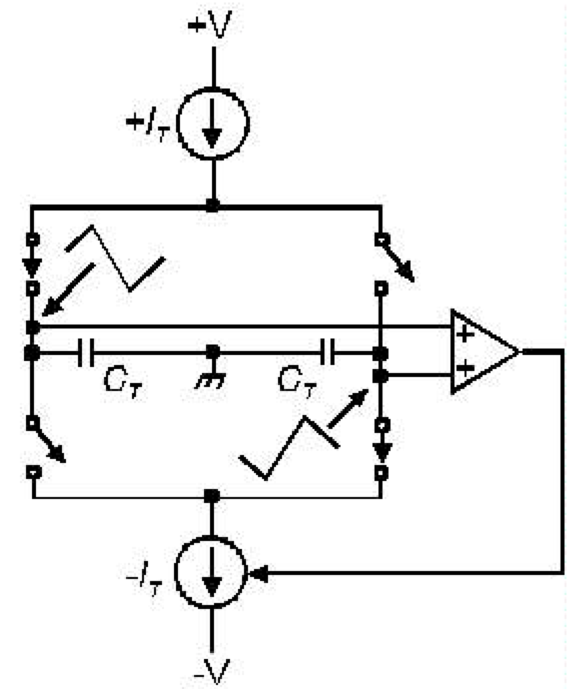


As a TM500 plug-in, the FG506 derived its power from a TM500 mainframe. This is not necessary: a stand-alone unit can be packaged with a supply providing the indicated unregulated voltages. Also, the crowded front-panel typical of TM500 equipment can be repackaged for more finger room.

The overall scheme for the FG506 is similar to second-generation FGs, which switched bipolar current sources to charge and discharge a timing capacitor to generate a triangle-wave. The switching activity produced the square-wave, and the triangle-wave, shaped by a suitable sine-converter circuit, produced the third FG waveform.

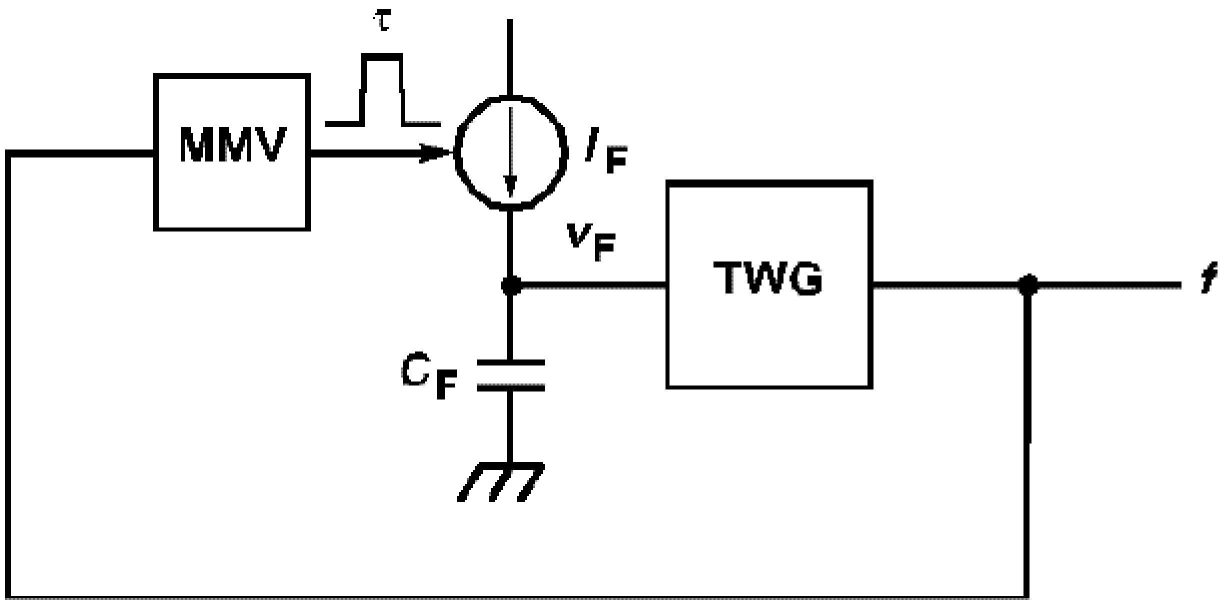
Triangle-Wave Generation

The FG506 has three unusual circuits concepts. The first is a novel way to maintain triangle-wave time symmetry. This is important in that it affects the distortion of the sine-wave. The triangle-wave generator (TWG) produces a differential triangle-wave by switching the $+I_T$ timing current into one of two timing capacitors, as shown below. The $-I_T$ source produces an opposing ramp on the other timing capacitor. This source is controlled by the symmetry error between the two ramps, so that the negative-going ramp follows the positive-going ramp, thereby causing the slope of the ramps to be equal in magnitude though opposite in polarity. Because this slope-follower scheme uses a feedback loop, it will not be able to generate waveforms as quickly as those for which $-I_T$ is open-loop and matched to $+I_T$. The relatively low maximum frequency of the FG506 poses no problem for adequate loop response.



Sweep Generator

For frequency-response or Bode magnitude plots, an exponentially-swept VCF directly produces a log-frequency plot on an oscilloscope display. A simple way of producing a "logarithmic" sweep (so it appears on the oscilloscope) is shown below. The switches of the



TWG loop produce a square-wave which is picked off and used to trigger an MMV on each cycle of the FG output. It gates on a current source for a fixed time, transferring a fixed charge to the VCF capacitor C_F. This increments v_F by a fixed amount, causing the output frequency to increment. As the frequency increases, the rate of increase of v_F increases along with it and is exponential. The resulting frequency sweep, when displayed, is stepwise logarithmic.

During a given time interval, Δt, n periods of the output occur. Then:

$$\frac{\Delta v_F}{\Delta t} = \frac{n \cdot (I_F \cdot \tau / C_F)}{n \cdot T} = f \cdot \left(\frac{I_F \cdot \tau}{C_F} \right)$$

In the limit, for small Δv_F or infinite n:

$$\lim_{n \to \infty} \frac{\Delta v_F}{\Delta t} = \frac{dv_F}{dt} = \left(\frac{I_F \cdot \tau}{C_F} \right) \cdot f$$

As a voltage-to-frequency converter (VFC):

$$f = k_F \cdot v_F$$

Substituting into the previous equation and solving the differential equation results in:

$$v_F = v_F(0) \cdot e^{(I_F \cdot \tau / C_F) \cdot k_F \cdot t}$$

and:

$$f = f(0) \cdot e^{(I_F \cdot \tau / C_F) \cdot k_F \cdot t}$$

The sweep-rate constant is $(I_F \cdot \tau / C_F) \cdot k_F$, and the sweep time is:

$$t_{SWP} = \frac{\ln(f / f(0))}{(I_F \cdot \tau / C_F) \cdot k_F}$$

where, $f(0)$ is the starting frequency and f the ending frequency.

The VFC constant, k_F, can be found from the TWG parameters. For a triangle-wave amplitude of V_M, the slope is:

$$\frac{V_M}{T/2} = \frac{I_T}{C_T} = \frac{v_F / R_T}{C_T} \Rightarrow f = \left(\frac{1}{2R_T \cdot C_T} \cdot \frac{1}{V_M} \right) \cdot v_F \Rightarrow k_F = \frac{1}{2R_T \cdot C_T} \cdot \frac{1}{V_M}$$

where, v_F develops I_T through R_T, and C_T is the timing C.

For construction of an FG506, these design equations are not needed, though they can be useful in making design modifications to the frequency sweep.

Sweep Frequency Control

The start and stop frequency knobs set voltages at the inputs of the start and stop V/I converters. They determine the timeouts of MMVs triggered by the TWG square-wave. The MMV output edges and levels are input to MSI logic -- 5 quad gate ICs -- that outputs the sweep direction (up or down/retrace). As shown in the block diagram this logic line is input to the sweep generator for discharging C_F. The line is also used, when so switched, to turn off the output amplifier to blank the retrace sweep.

In the following two parts, circuit diagrams are presented and explained, ECB parts layout suggested, and some subtleties revealed.