Bang-Bang Loop Analysis

A simplified version of the clock recovery phase-locked loop of the G-link chipset is shown in Fig 1. Only the transition sampling latch is shown, and the input is assumed to be a square wave at the same frequency as the VCO.

The VCO is controlled through a loop filter that consists of the sum of an integral signal and a proportional signal. Because the phase detector is quantized, the VCO frequency switches between two discrete frequencies, causing the VCO to ramp up and down in phase, thereby tracking the incoming signal phase.

If the loop is properly designed, the system can be considered to be composed of two noninteracting loops. These are the paths labeled proportional branch and integral branch in Fig. 1. The first loop includes the connection of the phase detector to the VCO input through a proportional attenuator, while the second loop drives the VCO through an integrator.

The proportional signal tunes the VCO, causing the output of the phase detector to switch rapidly between 1s and 0s at a fairly high frequency. Other than the dc component, the bulk of the phase detector output signal spectrum falls outside the effective passband of the integrator branch of the loop. Thus the integrator branch operates on just the dc component of the phase detector output. Its job is to servo the center frequency of the VCO so that the two discrete VCO frequencies programmed by the proportional input will always bracket the frequency of the incoming data signal. This frequency adjustment occurs so slowly that it does not materially affect the operation of the high-frequency bang-bang portion of the loop.

Proportional Branch

To simplify the analysis of the first branch of the loop in Fig. 1, the integrator output can be replaced with a constant reference voltage so the proportional tuning input will cause the VCO to bracket the incoming frequency. The VCO will then run at two discrete frequencies: at a frequency slightly higher than the incoming data, thereby advancing the phase, or at a lower frequency, thereby retarding the phase.

If the incoming frequency is midway between these two discrete frequencies, the loop will switch between the two frequencies with approximately a 50% duty cycle. If the incoming frequency is slightly higher than the nominal VCO center frequency, the duty cycle will shift such that the loop will spend a higher percentage of time at the high frequency than at the low frequency. In general, it can be shown that the duty cycle present at the output of the phase detector is proportional to the difference in frequency between the incoming signal and the nominal VCO center frequency.

Integral Branch

The second branch of the loop contains the integrator. Because the integrator effectively filters out the oscillatory portion of the phase detector output and only reacts to the average value of the phase detector output stream, the proportional branch of the loop can be ignored here by replacing the phase detector with a virtual frequency detector. The integrator extracts the dc component and thereby tunes the center frequency of the VCO so that it is always equal to the incoming data rate.

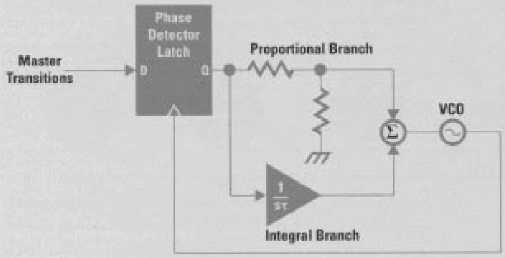

Fig. 1. Simplified version of the phase-locked loop. For analysis, the loop can be considered a combination of two noninteracting loops: a proportional branch and an integral branch.

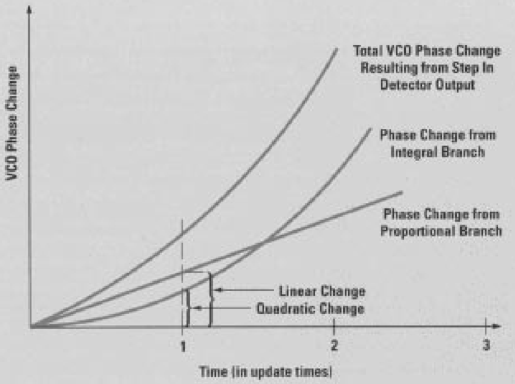

Fig. 2. Contributions to VCO phase changes. Stability factor is the linear phase change divided by the quadratic phase change in the same time.

In a conventional linear phase-locked loop, the loop error signal is proportional to phase error but is used to control the VCO frequency. This introduces an integration in the loop transfer function. This integration, in conjunction with the loop filter, creates a second-order feedback loop. Such loops can exhibit an underdamped response to changes in input phase, leading to an undesirable exponential buildup of jitter in systems with long cascades of repeaters.

In the G-link phase-locked loop, the phase-detector dc component is proportional to frequency rather than phase. Because the the frequency of the VCO is controlled by a frequency error signal rather than a phase error signal, no extra integration appears in the loop transfer function. This means that no jitter buildup results from the action of the integral branch of the loop. The jitter statistics are simply dominated by the hunting behavior of the high-frequency proportional branch of the loop.

Loop Stability

To reach a qualitative understanding of the loop behavior, the two branches of the loop were assumed to be noninteracting. For this assumption to be valid, certain conditions must be met.

It is important that the loop be set up so that, between phase samples, the action of the proportional branch of the loop dominates over the action of the integral branch. This can be verified by creating a step change from the phase detector and tracking its effect on both halves of the loop. Fig. 2 shows the contributions to the VCO phase change. In the proportional path, the VCO is programmed to make a small step change in frequency, which causes a linear ramp in the phase error. In the integral path, the integrator programs a linear ramp in VCO frequency, which causes a quadratic walk-off in the VCO phase.

The ratio of these effects at the end of one frame update time gives a figure of merit for the loop design. The phase change from the proportional branch of the loop must be greater than or equal to the phase change from the integral branch of the loop for the system to be stable. In the G-link design, this stability ratio is designed to be always greater than 10.

Richard C. Walker
Principal Project Engineer
Hewlett-Packard Laboratories