NASA TECH BRIEF

NASA Pasadena Office

Third-Order Phase-Locked Loop Receiver

The problem:

As the more-difficult deep space missions come into being, there is a corresponding stringency of requirements placed on the tracking instruments. To date, second-order phase-locked receivers, used both in spacecraft and in ground tracking stations, have performed so satisfactorily that there has been practically no reason to consider a more complicated system. The deep space missions, however, produce Doppler rate profiles that may cause up to 30° steady-state phase errors in the unaided second-order loops. Such errors in the second-order receivers decrease the efficiency with which command or telemetry data are detected (by 1.25 dB at 30°). In addition, they make acquisition of lock difficult and faulty and increase the likelihood of cycle slipping and loss of lock.

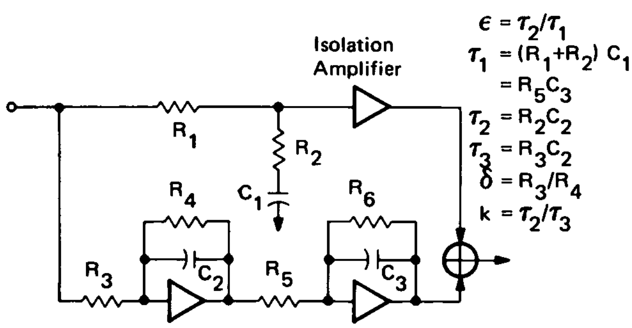


Figure 1. Third-Order Loop Filter Which Is An Extension of Second-Order Loop by Addition of Two Integrators.

The solution:

A simple third-order extension to the present second-order systems extends their Doppler tracking capabilities. In addition, it widens the receiver pull-in range, decreases pull-in time, lowers the voltage-controlled oscillator (VCO) noise (determining when no signal is present), and lessens the susceptability to VCO drift.

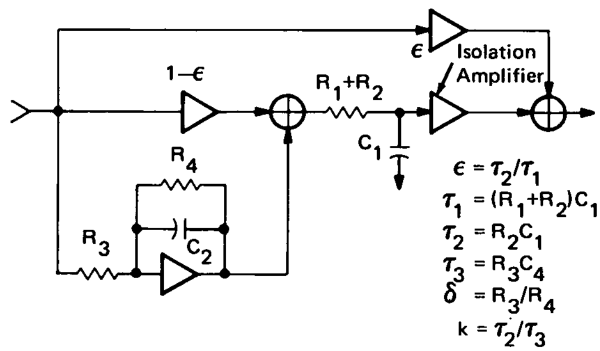


Figure 2. Third-Order Loop Filter Which Is Not An Extension of Usual Second-Order Loop.

How it's done:

The loop filter under consideration may be synthesized in several ways, three designs of which are shown in Figures 1, 2, and 3, respectively. They have the same transfer function (see figures for parameter definition):

$$F(s) = \frac{1+\tau_2 s}{1+\tau_1 s} + \frac{1}{(1+\tau_1 s)\,(\delta+\tau_3 s)}$$

With the same loop transfer function, the designs operate identically once the loop is locked; they differ in their lock-in transient behaviors, however, because of the possibly different initial capacitor voltages. If all capacitors are shorted at time t = 0, they are again identical, within the limits introduced by hardware imperfections.

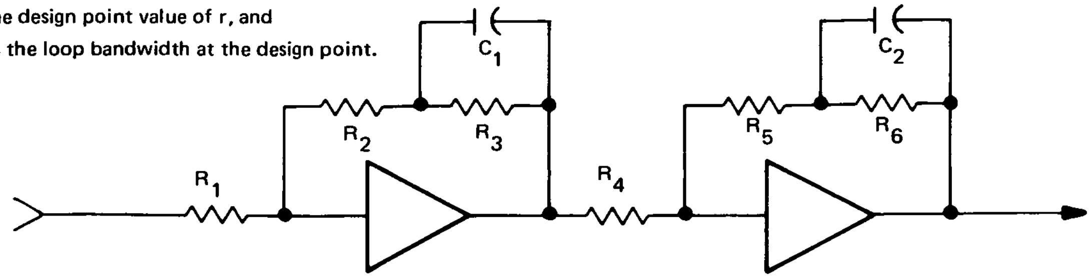
The two-sided noise bandwidth in the simplified, but usual, case of $\epsilon = \tau_2/\tau_1 \ll 1$ and $\delta \ll 1$ is given by

$$w_L = \frac{r}{2\tau_2}\left(\frac{r-k+1}{r-k}\right)$$

where $r = Ak\tau_2^2/\tau_1$ is set equal to 2, with A being the rms signal amplitude and k being the loop gain. The parameter k is the time-constant ratio τ_2/τ_3. As compared with the loop bandwidth formula of the second-order loop, the simplified expression above is only

(continued overleaf)

Note: r_0 is the design point value of r, and W_{L_0} is the loop bandwidth at the design point.



$$r_0 = 3.375 = Ak\left(\frac{1+\delta}{\delta}\right)\frac{\tau_2^{\,3}}{\tau_1^{\,2}} \qquad \tau_2 = \frac{r_0}{W_{L_0}}\,\frac{(4\,r_0+3)}{(4\,r_0-1)}$$

$$\tau_1 = R_3C_1 = R_6C_2 \qquad \delta \approx \frac{R_1R_4}{(R_2+R_3)\,(R_5+R_6)}$$

Figure 3. Third-Order Loop Filter With Series Integrator (Critically Damped, at k=0.25).

slightly increased in complexity, and of course the two merge to the same result as k approaches 0. The primary determining factors of w_L are still τ_2 and r, just as in the second-order loop. The phase error variances of any two loops due to input noise are of course the same as long as their loop bandwidths are the same.

The theory developed for computing the pull-in range of a second-order loop is easily extended to account for effects in the third-order loop; there is an enhancement in the acquisition range by approximately the square root of the added integrator dc gain. In fact, experimental evidence verifies this formula exceedingly well, all the way out to the point where IF filtering or minute equipment bias imperfections begin to limit the loop pull in.

Due to imperfect integrations, there are steady-state phase errors that build up because of instantaneous frequency detuning and the rate of change of this detuning. Compared with the corresponding expression for a second-order loop, the steady-state error due to an instantaneous frequency offset is reduced by a factor of about δ, and the error caused by a frequency rate is diminished by a factor of about $\delta+(\epsilon/k)$. Such a comparison reflects the desirability not only of making ϵ and δ very small but also of keeping k as large as other factors will permit.

To minimize the possibility that acquisition is faulty, it is necessary that damping be critical or beyond; to minimize steady-state error once lock is achieved, k should be as large as possible. These two conditions are met in slightly different ways according to the type of signals to be tracked. If the design is to be for signals of a fixed level, then k should be set to k_{max}=0.33 and r should be set to produce critical damping at that level, r_0=3.0. If the design is to be for signals of various intensities, then k should be made equal to k_0=0.25, and r should be set for critical damping at the weakest-expected signal level to ensure that the roots are never underdamped, r_0=3.375.

Note:

Requests for further information may be directed to:

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Patent status:

This invention has been patented by NASA (U.S. Patent No. 3,704,671). Inquiries concerning nonexclusive or exclusive license for its commercial development should be addressed to:

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