AN ANALYSIS OF A LOW INFORMATION RATE TIME CONTROL UNIT

Lowell Fey, James A. Barnes, and David W. Allan

National Bureau of Standards, Boulder, Colorado

Timing systems which are driven by unadjusted quartz crystal oscillators accumulate errors due to oscillator frequency instability. To realize maximum timekeeping precision, assuming a frequency calibration is available intermittently, the oscillator frequency must be correspondingly readjusted or the clock must be reset, or a bookkeeping method employed to systematically account for errors. At best, none of these procedures is as satisfactory as having a stable frequency available continuously; besides being time consuming, the above expedients always introduce a possibility for error. In an operational system, the problem is compounded because coordination is required among a number of people in a number of stations. To minimize these disadvantages and in some cases improve accuracy, a method of operation which retains oscillator synchronization as automatically as possible is desired.

In first approximation, to keep separately located clocks in synchronism, it is only necessary that their driving oscillators operate at the same nominal frequency. As shown by Barnes,[1] this specification is not sufficient because of the occurrence of a particularly troublesome low frequency (flicker) noise in oscillators. This noise causes a statistical divergence in the times kept by clocks driven by separate oscillators even though their frequencies are nominally the same. For clock synchronism over an indefinitely long period, their driving frequencies must be locked together continuously. Within the same laboratory, this is not difficult to accomplish; the problem of interest is to maintain remotely located clocks in synchronism. Practical methods for arbitrary locations involve some type of radio propagation. The limitations of high frequency broadcasts such as those from WWV, are well-known to prevent synchronism to better than about 1 millisecond. With VLF propagation, however, ionospheric conditions are sufficiently stable to permit phase comparison, and thus synchronization, between oscillators at receiver and transmitter. Unattended operation of such a system is made impractical by diurnal shifts in received phase, making visual interpretation necessary to extract frequency comparison information from a record of received carrier phase compared to local oscillator phase. In doing this, the most reliable data results if phase difference is determined for the most stable period each day. Generally, this period is that of a few hours near midday on the propagation path; during the night, oscillator phase is degraded by increased propagation fluctuation and a phase offset error occurs as a result of sunrise and sunset diurnal phase changes. In order to overcome these difficulties as well as to permit compensation for local oscillator frequency drift without step frequency adjustments, the concept of a multiple loop servo system has been developed.

Such a system evolves from a single loop system such as used in VLF phase tracking receivers as follows. The conventional idealized single loop servo diagram is illustrated in Figure 1. Here the reference phase $\omega_o t$ is assumed to result from a constant angular frequency, ω_o, while the local oscillator phase is equal to $\omega_o t$ plus a small difference $\Phi(t)$. The function of the servo loop is to maintain the corrected phase output from the local oscillator, Φ_{out}, in agreement with the reference phase, $\Phi_{ref.}$. This is done by integrating the error between these two phases with respect to time to produce a rate of change of phase in a direction that will reduce the phase error. A step function error will thus produce a correction which decreases as e^{-At}. The time constant associated with this loop is seen to be $\tau = \frac{1}{A}$. If instead of a step function phase error, a frequency difference, $\Delta\omega$, exists between reference and local oscillator, the uncorrected phase errors will increase linearly with time. The action of the feedback loop will then be to supply a continuous phase correction while operating, of necessity, with a steady state phase error of magnitude $\frac{\Delta\omega}{A}$. The addition of a second loop will improve this situation as shown in Figure 2.

If a frequency difference, $\Delta\omega$, exists between reference and local oscillators, the phase error will be corrected as before with time constant τ_1. At the same time the second loop integrator also contributes an error correction, reducing the correction necessary by the first loop until, at steady state, all the correction is supplied by the second loop and no residual error is required as input to the first integrator. In effect, an error different from zero for finite length of time has been integrated to a constant by the first integrator. This constant input to the second integrator produces an output correction which has the desired property of increasing linearly with time. Since such a system, now has the possibility of being unstable, the time constants $\tau_1 = \frac{1}{A_1}$ and $\tau_2 = \frac{1}{A_2}$ must be adjusted, as treated in the usual servo theory,[2] to provide stability and optimum transient response. After equilibrium has been reached, since no steady state phase error is required to actuate the servo loops, the reference may be removed and the output phase will continue to follow the reference phase even though a frequency difference exists between reference and local oscillator. Carrying this procedure one step further, a third loop may be added, extending the performance capability to that of compensating for a linear change in oscillator frequency, that is for oscillator drift. Then, as before, after equilibrium has been reached, the system will adjust itself so that the necessary oscillator drift correction is shared by the 2nd and 3rd loops with none required of the first loop. Consequently the output frequency will again continue to remain constant after the reference frequency has been removed. No further comparison to the constant reference frequency would be necessary if it were not for previously mentioned flicker fluctuations which perturb the oscillator frequency.

A realistic model of the behaviour of a good quartz crystal oscillator is to consider it as a source of frequency which increases at a constant rate, (drift), upon which is superimposed low frequency fluctuations known as flicker frequency modulation. This is a type of fluctuation having a power spectrum proportional to $\frac{1}{f}$ where f now refers to frequency components of the fluctuation. Thus $\Phi(t)$ is composed of a deterministic portion due to oscillator frequency offset from the reference and oscillator frequency drift plus a random portion due to flicker noise. The effect of flicker noise is to prevent a precise determination of oscillator frequency and drift rate since difficulty arises in separating flicker noise from drift.

This difficulty is illustrated in Figure 3. The ordinate, variance $\frac{(\Phi(t+\tau)-\Phi(t)}{\tau}$ presents a measure of spread, or fluctuation, in the phases (times) accumulated by an ensemble of oscillators as a function of sample time, τ, given on the abscissa. The negative slope region for short sample time corresponds to thermal or white noise and indicates that improvement in precision can be made by increasing measuring time. At times of the order of one second, flicker noise begins to predominate and has the effect of preventing further increase of precision with increasing sample time as well as producing the annoyance of a divergence of frequency fluctuation with increasing N, the number of samples. For illustration of differences, representative time series samples of various types of noise are shown in Figure (4). The most widely known is white noise, upper left, having the property of no correlation in time from point to point, and thus no frequency dependence in its power spectrum. At the lower left is flicker noise which has been shown[3] to apply to the frequency fluctuations of quartz crystal oscillators. It exhibits correlation in time and a $\frac{1}{f}$ frequency dependence. For further comparison successively higher correlation and frequency dependence are shown in random walk, $\frac{1}{f^2}$ and flicker walk $\frac{1}{f^3}$, (corresponding to the phase noise for $\frac{1}{f}$ FM), upper and lower right.

The servo design problem now becomes one of optimizing the loop time constants to provide the most stable operation in the presence of flicker noise, assuming periodic synchronization to a standard reference frequency. Since detailed analysis of a third-order feedback system requires numerical techniques even without treatment of noise, and servo running times of months or years are contemplated making real time experiments impractical, and since an efficient technique has recently been developed for computer generation of flicker noise,[4] it was decided to carry out the initial investigation entirely with the use of a digital computer.

Figure 5, obtained from a digital computer plot, illustrates the behaviour of the system with no noise input assuming a linear drift in local oscillator frequency and therefore a quadratic change in phase with time. Initial conditions were set so that the system correction rate was not adjusted to the quadratic input. Thus as time progressed, an error resulted which was reset to zero periodically, corresponding to synchronization of a real device to a constant reference frequency. The resulting transient response appears on the left. In this case time constants were such that the transient response became negligibly small after a few settings. Thereafter, prediction of the quadratic input was perfect, as theory requires, and the error remained at zero in the open loop condition.

Figure 6 shows the same system in steady state with only flicker noise and no oscillator drift input. The noise magnitude was taken to be that of a characteristic high quality quartz crystal oscillator, 2×10^{-12}, which means that the variance of frequency fluctuations with sample size N = 2 is expected to be 2×10^{-12}. The resulting errors are reset to zero daily, permitting only the small variation seen about the zero line.

Figure 7, again shows transient response assuming the same flicker noise plus a realistic frequency drift of 5×10^{-11} per day. If only a second order system were used, the daily errors shown would have remained constant at the initial value instead of dying out.

In all of these cases, the time constant of the first loop was taken to be negligibly small compared to the time constants of the other two loops, enabling phase error to be corrected to zero immediately upon application of a reference frequency. Comparison of behaviour using various 2nd and 3rd loop time constants under the above-mentioned realistic assumption for oscillator frequency drift and flicker noise, led to the choice of 1.1 days for the 2nd loop time constant and 20 days for the 3rd loop time constants as reasonably optimum. Figure 8 shows a steady state plot of error from such a system, with daily synchronizations for the first half of the running period. During the second half of the plot, synchronization to the reference was suspended. After 40 days, due to the effects of uncorrected flicker noise, the error had reached 12 microseconds, a value quite small compared to that resulting from an isolated free running oscillator.

Realization of a practical device could be accomplished either with an electromechanical system consisting of motors, gear reductions and ball and disk integrators or with an all electronic system using an electronic phase shifter such as developed by Barnes and Wainwright.[5]

In addition to using such a system with a VLF receiver and programming the reference to be applied during the best propagation time each day, the system could also be used in a continuously referenced mode in a laboratory with an atomic frequency standard. Should the standard fail the system could serve as a standby frequency source. Similarly in a laboratory which makes periodic calibration of oscillators that drive clocks, use of the device would reduce time fluctuations of the clocks over those occurring when oscillator frequency adjustments are made.

A different mode of operation might make use of synchronization by means of meteor burst propagation. In this case propagation between two points depends on reflections from dense ionization accompanying the frequent but random occurrence of meteors in the D region of the ionosphere. Using this method, Sanders,[6] et al., have observed microsecond stability over an 880-km path.

REFERENCES

1. J. A. Barnes, "Atomic timekeeping and the statistics of precision signal generators," Proc. IEEE, Vol. 54, p. 207, February 1966.

2. H. Chestnut and R. W. Mayer, Servomechanism and Regulatory System Design, New York, Wiley, 1951.

3. W. R. Atkinson, L. Fey, and J. Newman, "Spectrum analysis of extremely low frequency variations of quartz oscillators," Proc. IEEE (correspondence), Vol. 51, p. 379, February 1963.

4. D. Halford, to be published.

5. J. Barnes and A. Wainwright, "A precision pulse-operated electronic phase shifter and frequency translator," Proc. IEEE (correspondence) Vol. 53, p. 2143, December 1965.

6. W. R. Sanders, D. L. Albright, S. Tashiro, and D. N. March, "A meteor burst time synchronization experiment," to be published.

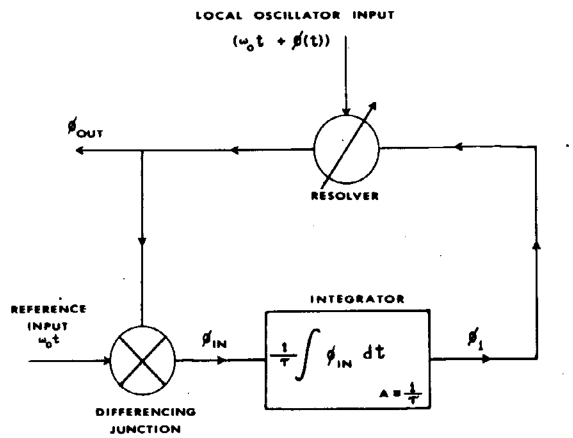

figure 1

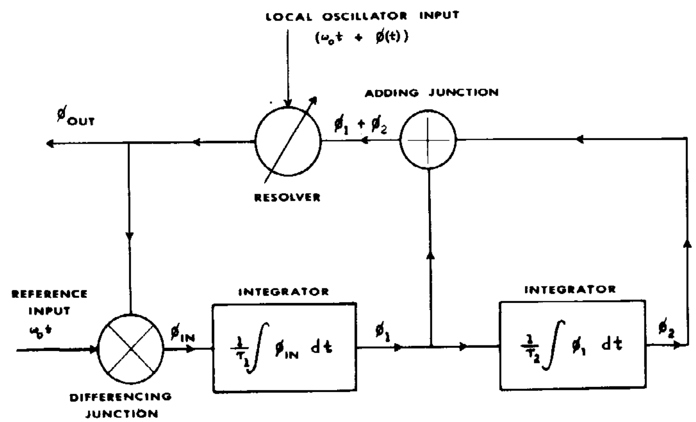

figure 2

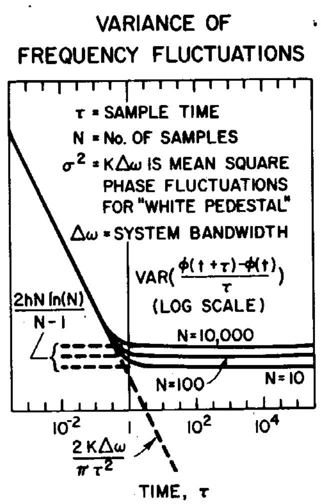

figure 3

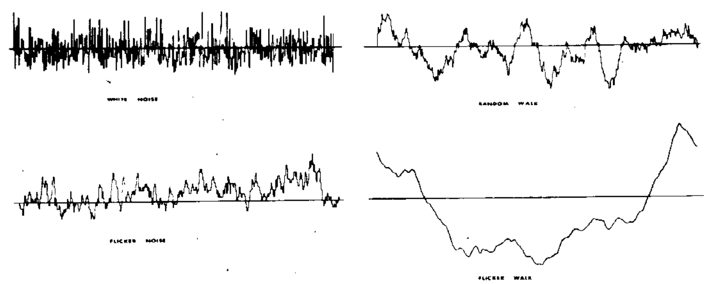

figure 4

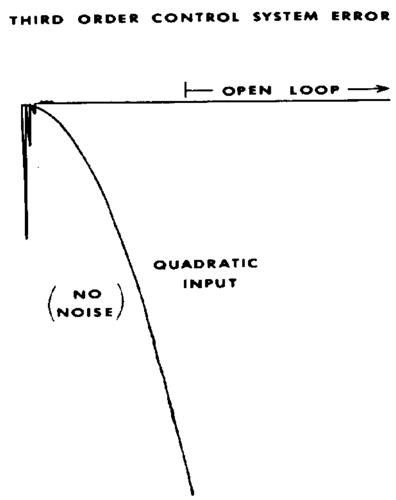

figure 5

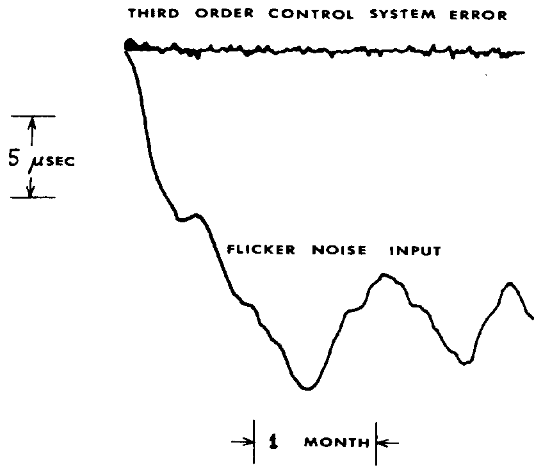

figure 6

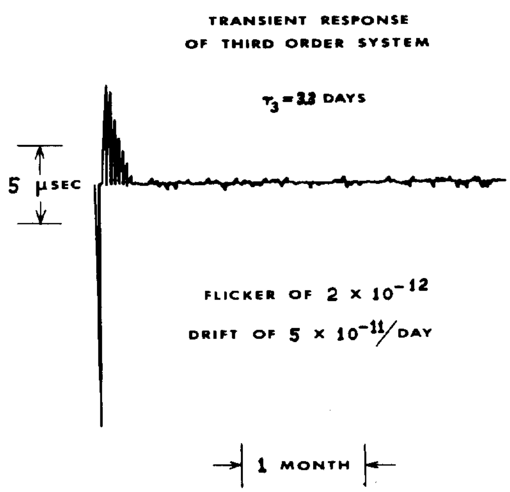

figure 7

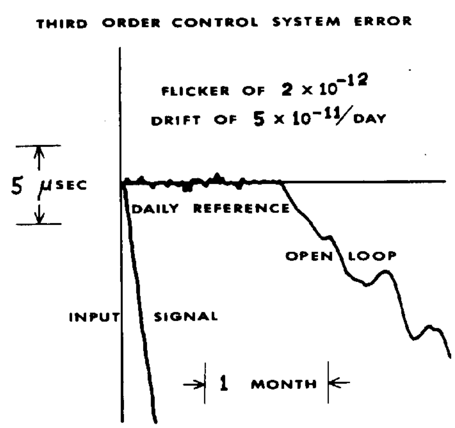

figure 8