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Compensation Of Impacts Of Thermal Shocks In Oscillator Controlled Circuits

J.Mannermaa[1], R.Ylinen[2], M.Kiviahde[2]
1) Nokia Mobile Phones,
P.O.Box 68, FIN-33721 Tre, Finland
2) University of Oulu, Systems Eng. Lab.,
P.O. Box 4300, FIN-90014 University of Oulu, Finland

Abstract-**Thermal shocks influencing onto oscillators will complicate the design of the phase and frequency locked loops. Due to thermal shocks the frequencies of crystals can run away from their nominal frequencies by tens or even more than 100 Hz in a second. Nokia Mobile Phones has made in the cooperation with Laboratory of System Engineering at the University of Oulu studies to manage the affect of thermal shocks in tracking loops. The results indicate that the influence of thermal shocks mostly can be compensated in the currently known conditions.**

I. INTRODUCTION

Presently and in the near future, there is expected a boom in the use of the different kind of tracking loops based on the phase or frequency locked loops (the PLLs and FLLs) controlled by the VCOs (Voltage Controlled Oscillator) or NCOs (Numerical Controlled Oscillator). The number of applications, in the sight already now, is remarkable as e.g. the CDMA (Code Divided Multiple Access) mobile phones, navigation satellite receivers (as those of the GPS ones, Global Positioning System) etc. Many of these items will be mass-volume products. Therefore, low costs are required, among the others in the component section. Nowadays, one of the most expensive is the crystal in the oscillator. In the future, as inexpensive crystals as possible will be applied. In fact, this means the poorer performance. Due to that, challenges for the manufacturing are emerged, since the disturbances created, for instance, by thermal shocks influencing onto oscillators will complicate the design of the phase and frequency locked loops. In practice, a thermal shock can enforce the frequency of the crystal to run away from its nominal frequency by tens or even more than hundred Hz in a second. Moreover, it must be emphasised that the thermal shock is not a (random) noise but a deterministic disturbance.

Nokia Mobile Phones has made in the cooperation with Laboratory of System Engineering at the University of Oulu studies to manage the affect of thermal shocks in tracking loops. The tracking loops were taken as an example due to that they are already commonly used e.g. in the CDMA-based mobile phones and GPS receivers. The influence of temperature was reduced by optimising the performance of the control loop filter in the tracking loop under the test. The needed theoretical, both analytical formulas and / or algorithms were derived for the system. Then the system was researched by simulating it both with a spread sheet program (Excel / Lotus) and Matlab/Simulink models applying a coded (Gold Code) input signal and different kind of loop filters (conventional-, (Extended) Kalman- and Fuzzy ones). The GPS civil C(oarse)/A(cquisition) –signal is applied to the MatLab/Simulink -simulations. The real signal is generated by modulating a sine carrier by a code and a navigational message but in these kind of studies it is unnecessary to take into account the navigational message. In this article, the studies concentrate on the conventional filters in this article. The non-linear filters considered as examples and for the comparison.

II. METHODS

There has been applied both theoretical and numerical methods to simulate the phenomenon and both analytical continuous and discrete formulas and / or algorithms were derived for the system(s).

Thermal shocks influence on the characteristics of crystal(s) causing the frequency to change in the oscillator(s) of a circuit. In some cases as the clocks of (pc-) computers the effect can be neglected but for example, in the different kind of receivers with the detection loops, as PLLs or FLLs, the phenomenon can create fatal malfunctions with the improper operation. This is emphasized, especially, with the (handheld) navigation satellite receivers whose input signals have been corrupted by different kind of phenomena as atmospheric ones and multipath etc. and the Signal-to-Noise -ratios are poor. In advance, in the most terminals, all used frequencies are generated by its master clock and thus, the thermal shock creates a systematic error into the operation(s) of the terminal.

The Signal-to-Noise –ratio can be regarded as poor when the signal power is lower than that of the respective thermal noise level (the bandwidth of the signal must be taken into account) which is considered as 0 dB in these studies. All signal powers are compared to this value and for example, the nominal GPS signal power is about 20 dB under the thermal noise level and thus denoted in the text by –20 dB. Every 3 dB doubles the power of a signal.

Let e.g. a PLL be used as an example. The system is presented in Fig. 1.

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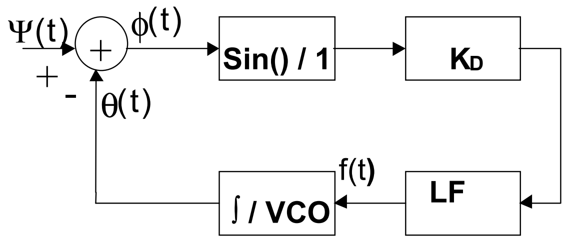


Fig. 1. Basic system.

In Fig. 1 the signals and blocks are determined as follows:
$\psi(t)$ is input signal,
$\theta(t)$ is estimate of input signal,
$\phi(t)$ is error signal,
$f(t)$ is control signal,
K_D is amplification of discriminator,
LF is loop filter,
VCO is Voltage Controlled Oscillator and
Sin() / 1 means the carrier or code tracking loop, respectively.

The input signal is considered to include the additive noise induced during the propagation of the signal and the deterministic and noise process components of the oscillator are induce to the system through the VCO (Voltage Controlled Oscillator).

The system is controlled by the loop filter (LF). There are some basic requirements and conditions which limit the type and construction of this filter. For example, an important characteristic of the conventional filters is their order since also the disturbances are created by a system of a certain order. A feedback system is able to eliminate the interferences whose highest order is smaller than that of the feedback system. This means that for example, a constant phase error can be eliminated by a filter of the first order or higher and the linear frequency change by a filter of the third order or higher etc.

If the disturbance of the oscillator due to the thermal shock is observed the highest influence is induced to the system as the change of frequency. But, the measured variable is the change of the phase (or the delay) that is the integral of frequency in the time domain and thus, the errors are proportional to the second power of time. This means that in practice, the effects due to thermal shocks can be eliminated totally only by the filters of the third order or higher. If a second order filter is used then a constant error will remain, though there are large differences in the value of this constant error when different kind of second order controllers are compared with each other.

A couple of different kind of solutions of conventional filters, referred as C1 (Case 1) and C2 (Case 2) in the later text, were applied in the studies based on references [1] and [2], respectively.

Some mathematical definitions have to be introduced to derive the algorithms applied simulations. For example, in the GPS receivers there are used two different kind of tracking loops called as carrier tracking loop and code tracking one. The basic operation in both types of tracking loops is the same one but the signal are sinusoidal in carrier loops and rectangular shaped pulses in code loops. The following definitions are used in the analysis of both loop type:

carrier tracking loop:

$$c(t) = \sin(\phi(t)) \,, \tag{1}$$

$$I = \int_0^t \sin(\phi(t)) \quad dt \,, \tag{2}$$

code tracking loop:

$$c(t) = \phi(t) \,, \tag{3}$$

$$I = \int_0^t \phi(t) \quad dt \,, \tag{4}$$

and integrator operator:

$$\frac{1}{p} = \int_0^t \bullet dt \,. \tag{5}$$

In C1, the Nth order system can be described as in Fig. 2.

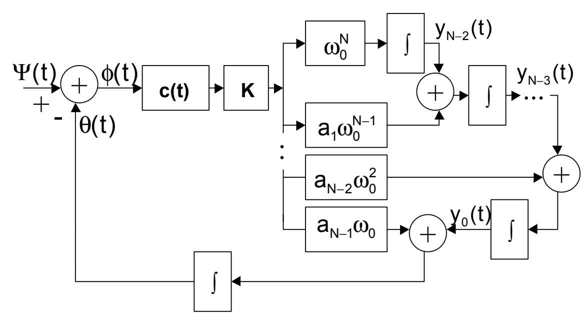


Fig. 2. Nth order system of C1

According to (1), (3) and Fig. 1, the variable $c(t)$ defines the type of the tracking loop.

For numerical simulations by spread sheet programs the states of the system are written as follows:

$$\frac{dy_{N-2}(t)}{dt} = K\omega_0^N \sin(\phi(t)) \,, \tag{7}$$

$$\frac{dy_{N-1}(t)}{dt} = Ka_1\omega_0^{N-1} \sin(\phi(t)) + y_{N-2}(t) \,, \tag{8}$$

$$\frac{dy_0(t)}{dt} = Ka_{N-2}\omega_0^2 \sin(\phi(t)) + y_1(t) \,, \tag{9}$$

$$\frac{d\phi(t)}{dt} = -a_{N-1}\omega_0 \sin(\phi(t)) - y_0(t) - \cdots - \frac{dN_c(t)}{dt} + \frac{d\Psi(t)}{dt} \,, \tag{10}$$

$$\phi(t) = -\sum_{m=0}^{N-1} a_{N-m-1}\,\omega_0^m \frac{1}{p^m}\, I\cdot K\,\omega_0 - N_c(t) + \Psi(t) \,, \tag{11}$$

where

$$a_0 = 1 \,. \tag{12}$$

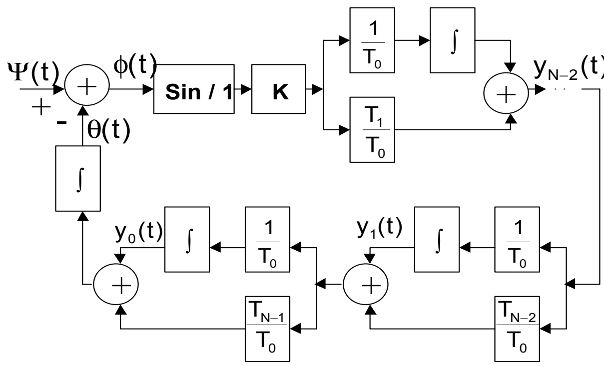


Fig. 3. *N*th order system of C2.

For numerical simulations by spread sheet programs the states of the system are written as follows:

$$\frac{dy_{N-1}(t)}{dt} = \frac{K}{T_0}\sin(\phi(t)) \,, \tag{13}$$

$$\frac{dy_{N-2}(t)}{dt} = \frac{T_{N-1}K}{T_0^2}\sin(\phi(t)) + \frac{1}{T_0}y_{N-1}(t) \,, \tag{14}$$

$$\frac{dy_0(t)}{dt} = \frac{K\prod_{m=2}^{N-1}T_m}{T_0^{N-1}}\sin(\phi(t)) + \cdots + \frac{T_2}{T_0^2}y_2(t) + \frac{1}{T_0}y_1(t) \,, \tag{15}$$

$$\frac{d\phi(t)}{dt} = -\frac{K\prod_{m=1}^{N-1}T_m}{T_0^3}\sin(\phi(t)) - \cdots - \frac{T_1}{T_0}y_1(t) - y_0(t) - \cdots - \frac{dN_c(t)}{dt} + \frac{d\Psi(t)}{dt} \,. \tag{16}$$

The solution is

$$\phi(t) = -\prod_{k=1}^{N-1}\left[1 + \frac{1}{T_k}\cdot\frac{1}{p^k}\right]\cdot I\cdot\omega_C - N_c(t) + \Psi(t) \,, \tag{17}$$

where

$$\omega_C = K\frac{T_1}{T_0}\frac{T_2}{T_0}\cdots\frac{T_{N-1}}{T_0} \,, \tag{18}$$

where

K is gain of system.

The linear systems are often presented by transfer functions. The transfer function is formed as a ratio of two Laplace (continuous time) - or Z (discrete time) –transformed variables of the system and the most popular ones are the ratios output/input or error/input. For example, in the case of C1 and C2 the ratios of error/input of the second and third order systems can be expressed as follows:

C1

Second order system

$$\frac{\phi(s)}{\Psi(s)} = \frac{s^2}{s^2 + sa_1K\omega_0 + K\omega_0^2} \,, \tag{19}$$

where

ω_0 is the natural angular velocity of the system.

Third order system

$$\frac{\phi(s)}{\Psi(s)} = \frac{s^3}{s^3 + s^2a_2K\omega_0 + sa_1K\omega_0^2 + K\omega_0^3} \,. \tag{20}$$

C2

Second order system

$$\frac{\phi(s)}{\Psi(s)} = \frac{s^2}{s^2 + sT_1\omega_s + \omega_s^2} \,, \tag{21}$$

where

ω_s is the natural angular velocity of the system.

Third order system

$$\frac{\phi(s)}{\Psi(s)} = \frac{s^3}{s^3 + s^2\omega_C + s2\alpha\omega_C^2 + \alpha^2\omega_C^3} \,, \tag{22}$$

where

$$\alpha = \frac{1}{\omega_C T_1} \,, \tag{23}$$

$$\omega_C = K\frac{T_1T_2}{T_0^2} \,. \tag{24}$$

The deterministic disturbance (input) induced by the VCO into the system is

$$N_c(s) = \frac{D}{2\;\, s^3} \,. \tag{25}$$

In the analytical case, the second order systems were studied and both versions can be expressed by the same formula with the different coefficients as follows:

$$\phi(t) = \frac{1}{a^2 + \omega_n^2}\left[1 - \frac{\sqrt{a^2 + \omega_n^2}}{\omega_n}e^{-at}\sin(\omega_n t + \varphi)\right] , \tag{26}$$

where

$$\varphi = \tan^{-1}\left(\frac{\omega_n}{a}\right) \,, \tag{27}$$

where in the C1 –case

$$a = \frac{1}{2}a_2\omega_0 \,, \tag{28}$$

$$\omega_n^2 = \omega_0^2\left(1 - \frac{1}{4}a_2^2\right) , \tag{29}$$

and in the C2 –case

$$a = \frac{1}{2}\omega_s^2 T_1 \,, \tag{30}$$

$$\omega_n^2 = \omega_s^2\left(1 - \frac{1}{4}\omega_s^2T_1^2\right) . \tag{31}$$

The analytical solutions of the third and fourth order systems are too complicated to be presented here due to different combinations of complex and / or real number solutions. The fifth or higher order systems are impossible to present in the closed analytical way since the poles of systems cannot be solved in the general form.

The important prosperities used to characterize the performance of a system, are among the others setting time, overshoot, rise time, stability and noise bandwidth. The most important one is the stability since the system operates properly only in the stable state. On the other hand, a system is always stable if its order is two or lower. The noise bandwidth is the second one due to the low Signal-to Noise – ratio in the applications in question. It should be as narrow as possible. The rise time is the third one since it indicates the ability of systems to follow the changes of input signal.

The stability terms of the systems of C1 and C2 are as follows:

$$Ka_1a_2 \geq 1\,, \tag{32}$$

$$K \geq \frac{2T_0^2}{T_1}\,, \tag{33}$$

respectively. In general, the noise bandwidth of a system is as follows:

$$B_L(\omega) = \frac{1}{2\pi}\frac{\int_0^{\infty}|H(\omega)|^2\,d\omega}{|H(0)|^2}\,. \tag{34}$$

It can be shown that for the systems under the study the noise bandwidths are as follows:

C1:

second order system

$$B_L = \frac{\omega_0(1+a_2^2)}{4a_2}\,, \tag{35}$$

third order system

$$B_L = \frac{\omega_0(a_1a_2^2 + a_1^2 - a_2)}{4(a_1a_2 - 1)}\,. \tag{36}$$

C2:

second order system

$$B_L = \frac{\omega_c}{4}(1+\frac{1}{T_1})\,, \tag{37}$$

third order system

$$B_L = \frac{\omega_c}{4}\cdot\frac{2\omega_cT_1+3}{2\omega_cT_1-1}\,. \tag{38}$$

Moreover, Kalman-filters and fuzzy controllers were applied to the studied tracking loops.

The state equations of the tracking loops are linear but the output equations are non-linear discriminator functions N. In the first order case the model of the code loop is

$$\frac{de}{dt} = \frac{d\tau}{dt} - \frac{d\hat{\tau}}{dt} = w - \frac{1}{f_o}f\,, \tag{39}$$

$$m = N(e+v, f)\,. \tag{40}$$

Here the delay τ is assumed to be a random walk with white noise input w. Furthermore, the noise in input signal is included to the model as a white phase (delay) noise v.

Now the error e can be estimated by the extended Kalman Filter

$$\frac{d\hat{e}}{dt} = -\frac{1}{f_o}f + \frac{P}{dN/de\,|_{(\hat{e},f)}\,\sigma_v^2}(m - N(\hat{e}, f))\,, \tag{41}$$

where

$$\frac{dP}{dt} = -\frac{P^2}{\sigma_v^2} + \sigma_w^2\,. \tag{42}$$

P converges to the solution

$$\bar{P} = \sigma_w\sigma_v\,. \tag{43}$$

The problem in this case is that the derivative in the denominator (Eq.21) can be zero, which causes instability. This is avoided by linearizing the output equation near the nominal solution e=0 instead of the neighbourhood of the current estimate.

The control can be designed by optimal control theory or by pole placement design. The optimal control is based, for instance, on minimization of a cost function

$$J = \int_0^T (qe^2(t) + rf^2(t))dt\,. \tag{44}$$

This leads to control law

$$f = -Ke = \frac{S}{f_or}e\,, \tag{45}$$

$$\frac{dS}{dt} = \frac{S^2}{f_o^2r} - q\,,\; S(T) = 0\,, \tag{46}$$

When T increases, S and K converge to the values

$$\bar{S} = f_o\sqrt{qr} \quad \text{and} \quad \bar{K} = -\sqrt{\frac{q}{r}}\,. \tag{47}$$

In advance, the used fuzzy solution was a PI –type controller with 5x5 triangular shaped input membership functions and 5 output membership functions. The control surface is described in Fig. 4.

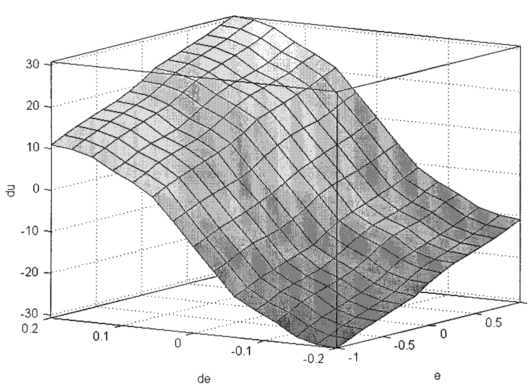


Fig. 4. Control surface of the used fuzzy controller.

To complete the studies a single channel GPS receiver was built by the MatLab/Simulink simulation tool. The large advantage of this tool was the creation of the noise process into the system and a reasonable way to control the signal-to-noise –

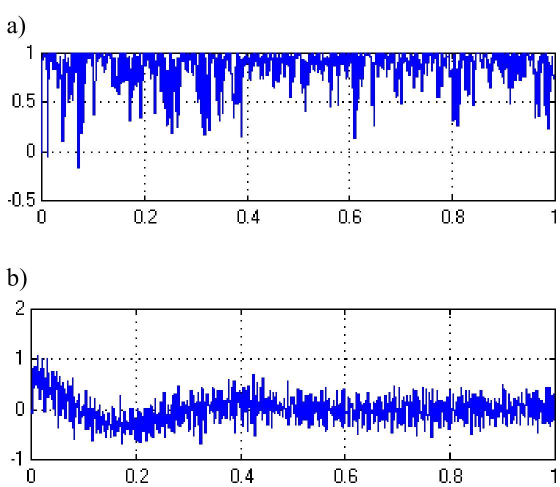
ratio by the running variance unit. The parameters and coefficients of the MatLab simulation models were tuned by the analytic and numerical models (spread sheet simulations).

The GPS C/A –signal carrier is transmitted at the frequency of 1575.42 MHz. The code is a sequence of 1023 rectangular shaped pulses called chips (the "noise bits" are called chips) with the code rate of 1 MHz and every single chip includes exactly 1540 carrier sine waves. Thus the signal generator of the loop (included in the block "VCO" in Fig. 1 is a PRN (PseudoRandomNoise) –generator that produces a known replica code. This replica is a sequence of rectangular pulses including a pre-determined amount of binary values of ±1, in the desired successive order. The navigational message is a sequence of bits and the duration of every single bit is 20 ms. The Signal-to-Noise –ratio of the received signal is low, about 20 dB under the thermal noise floor. The input of the process is the sky signal that is compared with the replica using correlation computations.

III. RESULTS

The amount of results was huge due to the large number of the combinations of different variables, parameters, coefficients and the input signals and /or noises. Even the slope the frequency change with the domain from 0 to over 100 Hz/s was pointed out rather wide. The maximum (slope of) frequency change as a function of time was searched after in every single test.

Some examples of the simulations by MatLab are shown in the Figs. 5-7. In all Figs, the horizontal axis is time in seconds, and in all a) –Figs. (lock detection) the values of the vertical axis have no unit (in general, the higher positive value the stronger lock exists), and in all b) –Figs the unit of the vertical axis is radian and in all c) –Figs it is parts of chip (in fact, e.g. the case of ±1/chip can be expressed by ±2π, too), in all d) –Figs, the unit is radian.



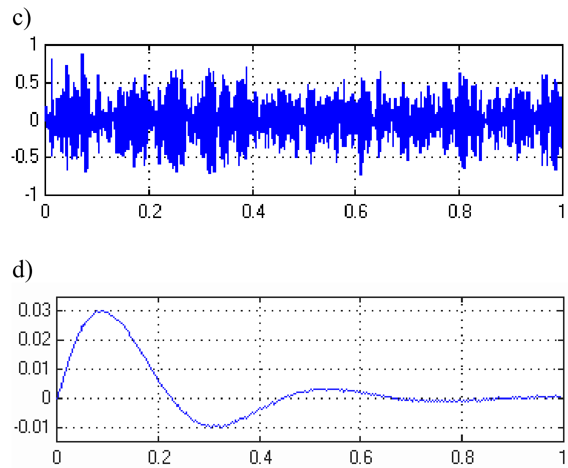


Fig. 5. A third order system of C1 with noise bandwidth of 18 Hz and the thermal shock of 30 Hz/s. The used gain (K) of the system was 5 and the input signal was the nominal GPS one, a) lock detection, b) discriminator output of code loop, c) discriminator output of carrier loop, d) filtered discriminator output of code loop.

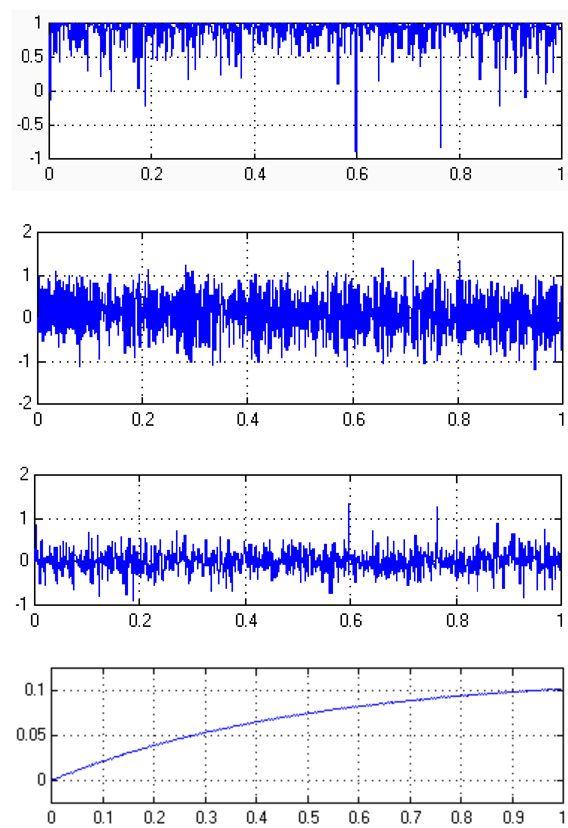


Fig. 6. A second order system of C2 with noise bandwidth of 18 Hz and the thermal shock of 30 Hz/s. The input signal was a GPS one with the signal-to noise-ratio 5 dB lower than in the nominal signal case, a) lock detection, b) discriminator output of code loop, c) discriminator output of carrier loop, d) filtered discriminator output of code loop.

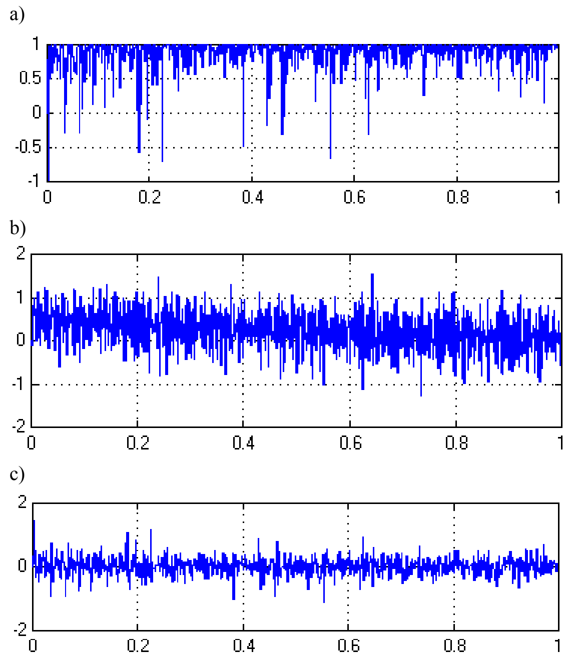


Fig. 7. A third order system of C2 with noise bandwidth of 1 Hz and the thermal shock of 30 Hz/s The input signal was a GPS one with the signal-to noise-ratio 5 dB lower than in the nominal signal case, a) lock detection, b) discriminator output of code loop, c) discriminator output of carrier loop.

In the following tables there are shown in the different kind conditions (Signal-to-Noise ratios and Noise bandwidths) the maximum time derivate of the frequency which the relative controller can compensate by maintaining the lock of the loop. In the same cell after the value of the maximum frequency derivative (separated by the comma) there is the relative gain of the used controller.

TABLE I
THE MAXIMUM FREQUENCY CHANGE AS A FUNCTION OF TIME IN THE SECOND ORDER SYSTEM OF C1. THE CONDITIONS ARE DESCRIBED BY THE SIGNAL-TO-NOISE-RATIO AND NOISE BANDWIDTH OF THE SYSTEM. THE RESULT CELL INCLUDES THE MAXIMUM FREQUENCY CHANGE AS A FUNCTION OF TIME AND THE RESPECTIVE GAIN SEPARATED BY COMMA, RESPECTIVELY.

S/N B_L	-20dB	-25dB	-30db	-35dB
1 Hz	31, 85	28, 85	10, 85	-
5 Hz	38, 20	31,19	17, 17	-
18 Hz	41, 6	29, 4	19, 3	-

TABLE II
THE MAXIMUM FREQUENCY CHANGE AS A FUNCTION OF TIME IN THE THIRD ORDER SYSTEM OF C1. THE CONDITIONS ARE DESCRIBED BY THE SIGNAL-TO-NOISE-RATIO AND NOISE BANDWIDTH OF THE SYSTEM. THE RESULT CELL INCLUDES THE MAXIMUM FREQUENCY CHANGE AS A FUNCTION OF TIME AND THE RESPECTIVE GAIN SEPARATED BY COMMA, RESPECTIVELY.

S/N B_L	-20dB	-25dB	-30db	-35dB
1 Hz	35, 90	23, 90	-	-
5 Hz	41, 20	28,20	15, 10	0, 1
18 Hz	39, 5	31, 5	20, 5	1, 1

TABLE III
THE MAXIMUM FREQUENCY CHANGE AS A FUNCTION OF TIME IN THE SECOND ORDER SYSTEM OF C2. THE CONDITIONS ARE DESCRIBED BY THE SIGNAL-TO-NOISE-RATIO AND NOISE BANDWIDTH OF THE SYSTEM. THE RESULT CELL INCLUDES THE MAXIMUM FREQUENCY CHANGE AS A FUNCTION OF TIME AND THE RESPECTIVE GAIN SEPARATED BY COMMA, RESPECTIVELY.

S/N B_L	-20dB	-25dB	-30db	-35dB
1 Hz	93, 550	61, 400	26, 200	0, 1
5 Hz	71, 70	56, 60	32, 50	0, 1
18 Hz	96, 17	67, 11	26, 8	-

TABLE IV
THE MAXIMUM FREQUENCY CHANGE AS A FUNCTION OF TIME IN THE THIRD ORDER SYSTEM OF C2. THE CONDITIONS ARE DESCRIBED BY THE SIGNAL-TO-NOISE-RATIO AND NOISE BANDWIDTH OF THE SYSTEM. THE RESULT CELL INCLUDES THE MAXIMUM FREQUENCY CHANGE AS A FUNCTION OF TIME AND THE RESPECTIVE GAIN SEPARATED BY COMMA, RESPECTIVELY.

S/N B_L	-20dB	-25dB	-30db	-35dB
1 Hz	84, 400	60, 350	10, 350	-
5 Hz	99, 135	30, 135	12, 10	0, 1
18 Hz	96, 20	66, 15	5, 15	0, 1

TABLE V
THE MAXIMUM FREQUENCY CHANGE AS A FUNCTION OF TIME IN THE SYSTEM CONTROLLED BY AN EXTENDED KALMAN FILTER. THE CONDITIONS ARE DESCRIBED BY THE SIGNAL-TO-NOISE-RATIO. THE RESULT CELL INCLUDES THE MAXIMUM FREQUENCY CHANGE AS A FUNCTION OF TIME AND THE RESPECTIVE GAIN SEPARATED BY COMMA, RESPECTIVELY.

S/N B_L	-20dB	-25dB	-30db	-35dB
5 Hz	105, 130	41, 120	18, 15	2, 3

TABLE VI
THE MAXIMUM FREQUENCY CHANGE AS A FUNCTION OF TIME IN THE SYSTEM CONTROLLED BY A FUZZY CONTROLLER. THE CONDITIONS ARE DESCRIBED BY THE SIGNAL-TO-NOISE-RATIO AND NOISE BANDWIDTH OF THE SYSTEM. THE RESULT CELL INCLUDES THE MAXIMUM FREQUENCY CHANGE AS A FUNCTION OF TIME AND THE RESPECTIVE GAIN SEPARATED BY COMMA, RESPECTIVELY.

….S/N B_L	-20dB	-25dB	-30db	-35dB
5 Hz	105, 108	67, 72	32, 55	2, 4

IV. CONCLUSIONS

The results indicate that, at the moment, the influence of thermal shocks can be compensated if the maximum slope of the frequency change is less than 100 Hz/s with conventional filters. However, this requires a careful design of loop filters which mainly alone control the changes in the input signal frequency and / or phase. It has also been found out that the performance is highly sensitive with respect to the filter parameters / coefficients. In particular, this can be seen in the durations and amplitudes of harmful transients caused by thermal shocks. Moreover, there is a surprisingly high probability that the system drifts into unstable conditions. The performance can be improved by the use of non-linear and adaptive loop filters that however, require the higher processing power.

As the results of Tables V and VI indicate, the lower Signal-to-Noise –ratio the more superior the non-linear filters are compared with conventional ones. Moreover, the fuzzy solutions seem to be easier and faster to design to achieve a high-level performance than the Kalman filters due to the smaller number of parameters. The results pointed out that the influence of the thermal shocks mostly can be compensated in the currently known conditions.

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