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(54) Title: CRYSTAL OSCILLATOR FREQUENCY CALIBRATION

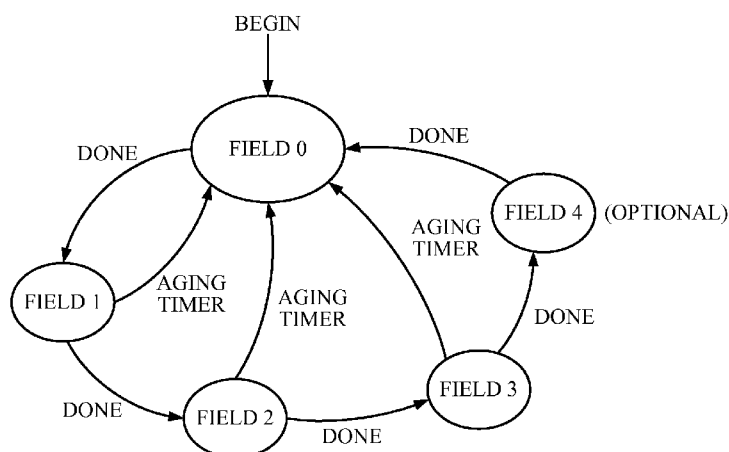


FIG. 4

(57) Abstract: Techniques are disclosed for estimating a frequency of a crystal oscillator based on temperature. In an embodiment, the oscillator frequency is computed using a polynomial approximation. Techniques are disclosed for deriving and periodically updating the coefficients used in the polynomial approximation.



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CRYSTAL OSCILLATOR FREQUENCY CALIBRATION

TECHNICAL FIELD

[0001] The disclosure relates to crystal oscillators and, more particularly, to techniques for estimating the frequency of crystal oscillators.

BACKGROUND

[0002] Crystal oscillators (XO) are used in communications devices as frequency sources. In a typical crystal oscillator, a quartz crystal having a nominal resonant frequency is coupled to an oscillator circuit that generates a signal having a nominal output frequency. In practice, the crystal's resonant frequency and the circuit's output frequency may vary over time due to factors such as temperature, aging, drive level and vibration.

[0003] In communications applications, frequency sources are typically required to meet strict accuracy requirements, thereby mandating the use of compensation schemes to improve the frequency accuracy of the crystal oscillator. Disclosed herein are techniques to estimate the crystal oscillator frequency, and account for variations of the crystal oscillator frequency over temperature.

SUMMARY

[0004] An aspect of the present disclosure provides a method for computing coefficients for use in a polynomial approximation of a crystal oscillator frequency, the polynomial comprising a term c_0' and a coefficient c_1' times a measured temperature T of the crystal oscillator, the method comprising measuring a first temperature T_1 and a corresponding oscillator frequency $F_m(T_1)$; measuring a second temperature T_2 and a corresponding oscillator frequency $F_m(T_2)$; computing the coefficient c_0' based on $F_m(T_1)$; and computing the coefficient c_1' based on T_1 , T_2 , $F_m(T_1)$, and $F_m(T_2)$.

[0005] Another aspect of the present disclosure provides a method for computing coefficients for use in a polynomial approximation of a crystal oscillator frequency, the polynomial comprising a term c_0' and a coefficient c_1' times a measured temperature T of the crystal oscillator, the method comprising entering a state FIELD0, operations in the state FIELD0 comprising computing the coefficient c_0' if the measured temperature T is within a first range of temperatures; and entering a state FIELD1, operations in the

state FIELD1 comprising computing the coefficient c_1' if the measured temperature T is within a second range of temperatures.

[0006] Yet another aspect of the present disclosure provides an apparatus for computing coefficients for use in a polynomial approximation of a crystal oscillator frequency, the polynomial comprising a term c_0' and a coefficient c_1' times a measured temperature T of the crystal oscillator, the apparatus comprising a temperature measurement unit for measuring a first temperature T_1 and a second temperature T_2 ; a frequency measurement unit for measuring corresponding oscillator frequencies $F_m(T_1)$ and $F_m(T_2)$; and a computing module for computing the coefficient c_0' based on $F_m(T_1)$, and for computing the coefficient c_1' based on T_1 , T_2 , $F_m(T_1)$, and $F_m(T_2)$.

[0007] Yet another aspect of the present disclosure provides a computer program product for computing coefficients for use in a polynomial approximation of a crystal oscillator frequency, the polynomial comprising a term c_0' and a coefficient c_1' times a measured temperature T of the crystal oscillator, the product comprising computer-readable medium comprising code for causing a computer to measure a first temperature T_1 and a corresponding oscillator frequency $F_m(T_1)$; code for causing a computer to measure a second temperature T_2 and a corresponding oscillator frequency $F_m(T_2)$; code for causing a computer to compute the coefficient c_0' based on $F_m(T_1)$; and code for causing a computer to compute the coefficient c_1' based on T_1 , T_2 , $F_m(T_1)$, and $F_m(T_2)$.

[0008] Yet another aspect of the present disclosure provides an apparatus for computing coefficients for use in a polynomial approximation of a crystal oscillator frequency, the polynomial comprising a term c_0' and a coefficient c_1' times a measured temperature T of the crystal oscillator, the apparatus comprising means for entering a state FIELD0, operations in the state FIELD0 comprising computing the coefficient c_0' if the measured temperature T is within a first range of temperatures; and means for entering a state FIELD1, operations in the state FIELD1 comprising computing the coefficient c_1' if the measured temperature T is within a second range of temperatures.

[0009] Yet another aspect of the present disclosure provides a computer program product for computing coefficients for use in a polynomial approximation of a crystal oscillator frequency, the polynomial comprising a term c_0' and a coefficient c_1' times a measured temperature T of the crystal oscillator, the product comprising computer-readable medium comprising code for causing a computer to enter a state FIELD0,

operations in the state FIELD0 comprising computing the coefficient c_0' if the measured temperature T is within a first range of temperatures; and code for causing a computer to enter a state FIELD1, operations in the state FIELD1 comprising computing the coefficient c_1' if the measured temperature T is within a second range of temperatures.

BRIEF DESCRIPTION OF DRAWINGS

[0010] FIG 1 shows a block diagram of a crystal 100 coupled to an oscillator circuit 110 to form a crystal oscillator.

[0011] FIG 1A plots a typical variation of a crystal's resonant frequency over temperature and crystal cutting angle.

[0012] FIG 2 depicts steps according to the present disclosure for estimating the coefficients c_0 , c_1 , c_2 , c_3 .

[0013] FIG 2A depicts an alternative embodiment of the present disclosure.

[0014] FIG 2B depicts an embodiment of a technique for measuring a frequency offset $F_m(T_1)$ at the receiver.

[0015] FIG 3A depicts a linear relationship between c_1' and c_2' denoted by $L_{1/2}$.

[0016] FIG 3B depicts a similar linear relationship between c_1' and c_3' that can be used to compute an estimate of c_3' from c_1' .

[0017] FIG 4 shows a state machine used to re-adjust an initially calibrated set of coefficients derived from, e.g., the procedure described in FIG 2.

[0018] FIG 5 shows an embodiment of operations performed during state FIELD0.

[0019] FIG 6 shows an embodiment of operations performed during state FIELD1.

[0020] FIG 7 shows an embodiment of operations performed during state FIELD3.

DETAILED DESCRIPTION

[0021] Disclosed herein are techniques to estimate the frequency of a crystal oscillator based on its measured temperature.

[0022] FIG 1 shows a block diagram of a crystal 100 coupled to an oscillator circuit 110 to form a crystal oscillator. The temperature of the crystal 100 is measured by temperature sensor 120, which generates a measured temperature T . The crystal oscillator generates an output signal 110a having a nominal reference frequency.

[0023] In an embodiment, the temperature T may be the temperature measured locally at the crystal. In an alternative embodiment (not shown), an additional temperature T_O

corresponding to the oscillator circuit local temperature may be measured and provided to improve the frequency estimate, as further described hereinbelow.

[0024] FIG 1A plots a typical variation of a crystal's resonant frequency over temperature and crystal cutting angle. It has been shown in the prior art that the relationship between crystal temperature and crystal resonant frequency may be approximated by a polynomial equation as follows (Equation 1):

$$F_x(T) = a_3 (T - T_0)^3 + a_2 (T - T_0)^2 + a_1 (T - T_0);$$

wherein T represents the crystal temperature, T_0 represents a fixed reference temperature, $F_x(T)$ represents the shift in crystal resonant frequency at temperature T relative to a nominal frequency F_{x0} , and a_1 , a_2 , a_3 are coefficients characterizing the particular crystal sampled. In general, the coefficients a_1 , a_2 , a_3 are determined by the crystal's physical properties, including its cutting angle. See, e.g., Arthur Ballato, "Frequency-Temperature-Load Capacitance Behavior of Resonators for TCXO Application," IEEE Trans. Sonics and Ultrasonics, Vol. SU-25, No.4, July 1978.

[0025] When the crystal 100 is coupled to the oscillator circuit 110 as shown in FIG 1, the frequency of the oscillator output signal 110a may vary over temperature as follows (Equation 2):

$$F_o(T, T_o) = c_3 (T - T_o)^3 + c_2 (T - T_o)^2 + c_1 (T - T_o) + c_0 + c_p (T_o - T_{o0}).$$

[0026] In Equation 2, T represents the crystal temperature, T_0 represents a fixed reference temperature, $F_o(T, T_o)$ represents the predicted frequency shift of the signal 110a at temperature T relative to a reference frequency F_{o0} , T_o represents the oscillator temperature, T_{o0} represents a fixed oscillator reference temperature, c_0 , c_1 , c_2 , c_3 are coefficients characterizing the oscillator output signal 110a's frequency dependence on crystal temperature, and c_p is a coefficient characterizing the oscillator output signal 110a's frequency dependence on oscillator temperature. The coefficient c_p may depend on, e.g., the capacitance loading the oscillator circuit.

[0027] In an embodiment, the coefficient c_p is derived by comparing a nominal F-T curve of the crystal provided by a crystal vendor with an F-T curve measured using a fully loaded crystal oscillator. The measurement may be done offline, e.g., in a laboratory.

[0028] Alternatively, to derive c_p , the crystal temperature may be fixed, while the oscillator temperature varied from a first temperature T_{o1} to a second temperature T_{o2} .

The corresponding oscillator output frequencies $F_o(T_{o1})$ and $F_o(T_{o2})$ may be measured. The coefficient c_p may then be estimated as follows (Equation 2a):

$$c_p = [F_o(T_{o1}) - F_o(T_{o2})] / (T_{o1} - T_{o2}).$$

[0029] Since the coefficient c_p is generally fixed for a given oscillator design, only a one-time measurement needs to be performed to estimate the coefficient. The estimate can subsequently be used for all implementations of the crystal oscillator.

[0030] According to an aspect of the present disclosure, techniques are provided to compute $F_o(T)$ according to Equation 2, using measured temperatures T and T_o , and estimates of the coefficients c_0 , c_1 , c_2 , c_3 .

[0031] FIG 2 depicts steps according to the present disclosure for estimating the coefficients c_0 , c_1 , c_2 , c_3 . In an embodiment, the steps depicted in FIG 2 may be performed in the factory.

[0032] At step 200, initial values for c_0 , c_1 , c_2 , c_3 are loaded from a memory. In FIG 2, the initial values loaded are designated as $c_{0_{init}}$, $c_{1_{init}}$, $c_{2_{init}}$, $c_{3_{init}}$, respectively. In an embodiment, $c_{0_{init}}$ is set to zero. In an embodiment, $c_{1_{init}}$, $c_{2_{init}}$, $c_{3_{init}}$ are set to the values of the coefficients a_1 , a_2 , a_3 , respectively, characterizing the crystal, according to Equation 1. The coefficients a_1 , a_2 , a_3 may be calculated from, e.g., data provided by the crystal vendor. In an embodiment, the coefficients a_1 , a_2 , a_3 may be estimated by averaging data from multiple crystal samples as provided by the crystal vendor. Alternatively, the coefficients a_1 , a_2 , a_3 may be estimated from a nominal F-T curve provided by the crystal vendor.

[0033] Returning to FIG 2, at step 202, the temperature T_1 of the crystal at an arbitrary time t_1 is measured, e.g., using temperature sensor 120 in FIG 1. Also measured is the corresponding oscillator frequency offset $F_m(T_1)$ from the reference frequency F_{o0} . In an embodiment, the frequency offset $F_m(T_1)$ may be measured by injecting a single tone of known frequency F_1 into a receiver, tuning the crystal oscillator nominally to the frequency F_1 , and observing the frequency of the signal after downconversion, as depicted in FIG 2B. The frequency of the signal after downconversion can be used to derive the frequency offset $F_m(T_1)$. Note one of ordinary skill in the art will realize that for simplicity, certain blocks have been omitted from the frequency measurement setup depicted in FIG 2B, such as amplifiers and/or other filters.

[0034] At step 204, an estimated coefficient $c0'$ is computed based on the information gathered at step 202. In an embodiment, the estimated coefficient $c0'$ is computed as follows (Equation 3):

$$c0' = Fm(T1) - F_{init}(T1),$$

wherein $F_{init}(T1)$ is computed by substituting the initial coefficient estimates $c0_{init}$, $c1_{init}$, $c2_{init}$, $c3_{init}$ into Equation 2, i.e., (Equation 4):

$$F_{init}(T1) = c3_{init} (T1 - T_0)^3 + c2_{init} (T1 - T_0)^2 + c1_{init} (T1 - T_0) + c0_{init}.$$

[0035] At step 206, the oscillator frequency at a second temperature $T2$ is measured, yielding $Fm(T2)$. The temperature $T2$ is preferably sufficiently separated from $T1$ to allow accurate estimation of the slope of the F-T curve, but sufficiently near $T1$ to minimize the effect of the second- and third-order terms. For example, the separation between $T1$ and $T2$ may be chosen to be at least one degree Celsius.

[0036] In an embodiment, the temperature $T2$ may be sampled after waiting a predetermined amount of time after time $t1$ at which $T1$ is sampled. In an alternative embodiment, a plurality of temperature-frequency data points may be sampled over a time interval, and the lowest temperature may be taken to be $T1$, and the highest temperature may be taken to be $T2$. In an embodiment, to further facilitate a sufficient separation between the temperatures $T2$ and $T1$, a heat source may be turned on after step 202, to raise the oscillator temperature. In an embodiment, the heat source may be a power amplifier.

[0037] At step 208, an estimated coefficient $c1'$ is computed. In an embodiment, $c1'$ may be computed as follows (Equation 5):

$$c1' = [Fm(T2) - Fm(T1)] / [T2 - T1].$$

[0038] At step 210, estimated coefficients $c2'$ and $c3'$ are computed. In an embodiment, $c2'$ and $c3'$ are assumed to be functions of $c1'$, such that specifying $c1'$ uniquely specifies $c2'$ and $c3'$. In an embodiment, $c2'$ and $c3'$ are assumed to be linearly related to $c1'$ as follows (Equation 6):

$$c2' = m_{c2'} * c1' + b_{c2'}; \text{ and}$$

$$c3' = m_{c3'} * c1' + b_{c3'};$$

wherein the linear coefficients $m_{c2'}$, $m_{c3'}$, $b_{c2'}$, $b_{c3'}$ may be empirically determined and/or pre-stored in memory.

[0039] FIG 3A depicts a linear relationship between $c1'$ and $c2'$ denoted by $L1/2$. In an embodiment, the coefficients $m_{c2'}$ and $b_{c2'}$ characterizing the linear relationship may be

derived from multiple crystal data samples as provided by the crystal vendor. These multiple data samples are shown in FIG 3A as a scatter plot superimposed on the line L1/2. Based on the data points, the estimated coefficients $m_{c2'}$ and $b_{c2'}$ may be determined according to predetermined optimality criteria, e.g., minimum mean square error between the line L1/2 and the data samples in the scatter plot.

[0040] FIG 3B depicts a similar linear relationship between $c1'$ and $c3'$ that can be used to compute an estimate of $c3'$ from $c1'$.

[0041] In an embodiment, only data from crystal samples manufactured by the same crystal vendor as the crystal being calibrated may be included to estimate the coefficients $m_{c2'}$, $b_{c2'}$, $m_{c3'}$, $b_{c3'}$. In an embodiment, crystal samples from multiple vendors may be included.

[0042] Returning to FIG 2, at step 212, an updated estimate $c0''$ for the coefficient $c0$ may be obtained based on the estimated coefficients $c0'$, $c1'$, $c2'$ and $c3'$ derived in steps 204, 208, and 210. In an embodiment, $c0''$ may be computed as $c0'' = Fm(T1) - F'(T1)$, where $F'(T1)$ is computed as follows (Equation 7):

$$F'(T1) = c3' (T1 - T_0)^3 + c2' (T1 - T_0)^2 + c1' (T1 - T_0) + c0'.$$

[0043] In step 214, the coefficients $c0$, $c1$, $c2$, $c3$ may be updated to the values of the computed coefficients $c0''$, $c1'$, $c2'$, $c3'$, respectively. In an embodiment, the updated coefficients may be stored in a memory.

[0044] FIG 2A depicts an alternative embodiment of the present disclosure. In FIG 2A, steps 202-212 are each performed a total of $N+1$ times to obtain multiple estimates of the coefficients $c0$, $c1$, $c2$, $c3$. Numbered steps in FIG 2A correspond to similarly numbered steps in FIG 2.

[0045] In FIG 2A, step 200 initializes the coefficients. In an embodiment, this may be done in the same manner as earlier described with reference to FIG 2. In addition, at step 200, an iteration index n is set to 0. Steps 202-212 proceed as described earlier with reference to FIG 2, with $[n]$ representing the computed coefficient corresponding to each iteration index. At step 213, the algorithm checks for whether the iteration index n has reached N . If not, then the algorithm increments n , and returns to step 202 for the next iteration. If n has reached N , then the algorithm proceeds to step 214.

[0046] Upon returning to step 202 for a subsequent iteration, steps 202-212 may be repeated to derive a set of coefficients $c0'[n]$, $c1'[n]$, $c2'[n]$, $c3'[n]$, $c0''[n]$ associated

with each iteration index n. In an embodiment, the set of coefficients derived for each iteration index n may be stored in memory for later processing.

[0047] In an embodiment, the coefficients c_0' , c_1' , c_2' , c_3' from all N+1 iterations may be combined to generate an estimate for the coefficients c_0 , c_1 , c_2 , c_3 . This may be done by averaging together the sets of estimated coefficients computed during the N+1 total iterations to produce one set of coefficients, as noted in step 214 of FIG 2A.

[0048] In another embodiment (not shown), an infinite impulse response (IIR) filter may be used to update the coefficients with each iteration, as follows (Equation 8):

$$[c_0, c_1, c_2, c_3]_{new} = \alpha [c_0, c_1, c_2, c_3]_{old} + (1 - \alpha) [c_0, c_1, c_2, c_3]_{current}; 0 < \alpha < 1$$

In this embodiment, $[c_0, c_1, c_2, c_3]_{old}$ is the running estimate of the coefficients, $[c_0, c_1, c_2, c_3]_{current}$ is the estimate of coefficients computed for the current iteration n, and $[c_0, c_1, c_2, c_3]_{new}$ is the updated estimate of coefficients.

[0049] In yet another embodiment, instead of averaging or IIR filtering the sets of estimated coefficients, a joint probability maximization method may be employed to derive an optimal set of coefficients based on the N+1 available sets of coefficients. For example, given the plurality of F-T data points sampled in the process of FIG 2A, an optimal set of coefficients c_{0opt} , c_{1opt} , c_{2opt} , c_{3opt} yielding a minimum mean-squared error between the F(T) and the sampled data points may be derived. In an embodiment, to simplify the search process, a linear relationship may be assumed between c_{1opt} and each of coefficients c_{2opt} and c_{3opt} , as described previously herein with reference to FIGs 3A and 3B.

[0050] One of ordinary skill in the art will note that not all coefficients c_0 , c_1 , c_2 , c_3 need to be estimated using the techniques depicted in FIGs 2 and 2A. For example, in an embodiment, only coefficients c_0 and c_1 are estimated, with the appropriate modifications made to the steps depicted in FIGs 2 and 2A. Such embodiments are contemplated to be within the scope of the present disclosure.

[0051] In an embodiment, the steps shown in FIGs 2 and 2A may be performed in the factory, prior to in-field operation of the oscillator circuit. Alternatively, the steps may be performed during in-field operation of the oscillator circuit.

[0052] In an embodiment, the steps depicted in FIGs 2 and 2A may be performed once during an initial calibration phase of a device utilizing the crystal oscillator, e.g., during assembly of the device at a factory. In alternative embodiments, the steps depicted in FIG 2 may be performed multiple times as needed.

[0053] In an aspect of the present disclosure, the estimates for coefficients c_0 , c_1 , c_2 , c_3 may be periodically updated during normal operation to maintain their accuracy over time. Disclosed hereinbelow are techniques to periodically update the coefficient estimates.

[0054] FIG 4 shows a state machine used to re-adjust an initially calibrated set of coefficients derived from, e.g., the procedure described in FIG 2. The re-adjustment may help mitigate the inaccuracies of factory calibration, as well as inaccuracies due to aging of the crystal and/or oscillator.

[0055] In FIG 4, the re-adjustment procedure begins at state FIELD0. In an embodiment, the state FIELD0 calibrates the coefficient c_0 . In an embodiment, the calibration of c_0 may be done according to operations described later herein with reference to FIG 5. State FIELD0 may transition to state FIELD1 when a predetermined set of conditions (labeled “Done” in FIG 4) are met.

[0056] State FIELD1 may calibrate coefficient c_1 , as well as c_0 . In an embodiment, the calibration of c_0 and c_1 may be done according to operations described later herein with reference to FIG 6. State FIELD1 may transition to state FIELD2 when a predetermined set of conditions are met. State FIELD1 may also transition back to state FIELD0 if an aging timer expires.

[0057] In an embodiment, the aging timer may track the amount of time elapsed since any coefficient has last been updated. The aging timer may be an electronic counter resident on a chip with the oscillator, or it may be a module that compares a time stamp stored during the last coefficient update with the current time stamp. In an embodiment, the aging timer can be set to expire two years after a last calibration.

[0058] Referring back to FIG 4, state FIELD2 may calibrate coefficient c_2 , as well as coefficients c_1 and/or c_0 . State FIELD2 may transition to state FIELD3 when a predetermined set of conditions are met. State FIELD2 may also transition back to FIELD0 if the aging timer expires.

[0059] State FIELD3 may calibrate coefficient c_3 , as well as coefficients c_2 , c_1 , and/or c_0 . In an embodiment, the calibration of c_3 , c_2 , c_1 , c_0 may be done according to operations described later herein with reference to FIG 7. State FIELD3 may transition to state FIELD4 when a predetermined set of conditions are met. Alternatively, state FIELD3 may transition back to FIELD0.

[0060] In an embodiment, state FIELD4 may be a sleep state. In the sleep state, the calibration mechanism may cease operation for a predetermined amount of time. In an embodiment, the predetermined amount of time may be one year.

[0061] Note in an embodiment wherein c_2 is approximately zero, state FIELD1 may skip FIELD2 and transition directly to state FIELD3 upon the predetermined set of conditions being met.

[0062] In an embodiment, the current state (i.e., FIELD0, FIELD1, FIELD2, FIELD3, or FIELD4) of the state machine is stored in nonvolatile memory, such that the state is preserved upon power-up or power-down of a device utilizing the crystal oscillator. In an embodiment, the crystal oscillator may be used in a wireless handset.

[0063] FIG 5 shows an embodiment of operations performed during state FIELD0. Note the embodiment illustrated in FIG 5 is not meant to limit the scope of the disclosure to any particular set of operations in FIELD0. Rather, one of ordinary skill in the art will realize that any steps used to update an estimate of the coefficients may be performed during any of the states FIELD0, FIELD1, FIELD2, FIELD3, and FIELD4. Such embodiments are contemplated to be within the scope of the present disclosure.

[0064] In state FIELD0, a counter n_0 for counting iterations of a loop is initialized to zero. At the first step 500, the state machine commences by waiting for a period of time FT_update_0 seconds. At the end of FT_update_0 seconds, the temperature T (e.g., in degrees Celsius) of the crystal is measured. At step 510, it is checked whether the temperature T falls within a range $|T - T_0| < T_1$ degrees. If yes, the current estimate $c_0[n_0]$ for coefficient c_0 is updated according to step 520. If no, then the state machine may return to step 500 to wait for another FT_update_0 seconds.

[0065] In an embodiment, T_0 is set to 30 degrees Celsius, and T_1 is set to 15 degrees Celsius.

[0066] In an embodiment, at step 520, the coefficient $c_0[n_0]$ may be updated by an IIR filter as follows (Equation 9):

$$c_0[n_0 + 1] = c_0[n_0] + \frac{(fm - f_{cal} - c_0[n_0])}{N_0};$$

where $c_0[n_0]$ is the estimated coefficient c_0 at iteration n_0 , fm is the actual measured frequency of the oscillator, f_{cal} is the oscillator frequency as estimated using, e.g., Equation 2 assuming the current (as of iteration n_0) set of coefficients, and N_0 is a weighting constant. Note for $n_0=0$, the coefficient $c_0[0]$ may be assumed to be the last c_0 stored in memory.

[0067] In an embodiment, the actual measured frequency of the oscillator f_m may be derived from an automatic frequency control circuit used in, for example, a receiver apparatus for code-division multiple access (CDMA). One of ordinary skill in the art will realize that there are alternative ways of measuring an actual frequency of the oscillator during in-field operation.

[0068] At step 530, n_0 is compared to a variable maxIterations_0 . If n_0 has reached a variable maxIterations_0 , then the state machine exits state FIELD0 and proceeds to the next state. If n_0 has not reached maxIterations_0 , then the state returns to step 500. FIG 6 shows an embodiment of operations performed during state FIELD1. In state FIELD1, a counter n_1 for counting the iterations is initially set to zero. At step 600, the state machine waits for a period of time FT_update_1 seconds. At the end of FT_update_1 seconds, the temperature T (e.g., in degrees Celsius) of the crystal is measured. At step 610, it is checked whether T falls within the range $T_1 \leq |T - T_0| < T_2$. If yes, then the current estimate $c_1[n_1]$ for coefficient c_1 may be updated according to step 620. If no, then the state proceeds to step 615, wherein the state machine checks whether T falls within the range. If yes, then the current estimate for c_0 is updated in step 625. If no, the state machine returns to step 600 to wait for FT_update_1 seconds.

[0069] In an embodiment, the operations in step 625 can be identical to the operations described with reference to step 520 in FIG 5. In an embodiment (not shown), an iteration index may also be provided for updating coefficient c_0 .

[0070] In an embodiment, T_2 is 30 degrees Celsius.

[0071] At step 620, the coefficient $c_1[n_1]$ is updated.

[0072] In an embodiment, $c_1[n_1]$ may be updated as follows. Given the current value of c_0 , candidate values of $c_1[n_1]$ may be assessed to determine the best c_1 candidate for the measured frequency and temperature, according to some optimality criteria. In an embodiment, the optimality criteria may include the error between a measured temperature-frequency pair and the computed temperature-frequency characteristic, assuming the current value of c_0 and a candidate value of c_1 . In an embodiment, the search for the best c_1 may be aided by assuming a linear relationship between c_1 and c_2/c_3 , e.g., as described with reference to FIGs 3A and 3B.

[0073] In an embodiment, once a best candidate c_1 is determined, that c_1 may be IIR filtered with a previous estimate of c_1 .

[0074] In another embodiment, the coefficient $c1[n1]$ may be determined by computing the following metric:

$$c1[n1] = \frac{Fm(T2) - Fm(T1)}{T2 - T1};$$

and then IIR filtering the computed coefficient $c1[n1]$ with a previous $c1[n1-1]$. In an embodiment, the IIR weighting constant can be 256.

[0075] At step 630, $n1$ is compared to a variable $maxIterations1$. If $n1$ has reached $maxIterations0$, then the state machine exits state FIELD1 and proceeds to the next state. If $n1$ has not reached $maxIterations1$, then the state returns to step 600.

[0076] In an embodiment, state FIELD2 may be implemented similarly to the states FIELD0 and FIELD1 previously described. In an alternative embodiment, FIELD2 need not be implemented if the coefficient $c2$ is predetermined to be close to zero. In this embodiment, state FIELD1 may bypass FIELD2 and directly transition to FIELD3.

[0077] FIG 7 shows an embodiment of the operations performed during state FIELD3. In state FIELD3, a counter $n3$ for counting the iterations is initially set to zero. At step 700, the state machine waits for a period of time $FT_update3$ seconds. At the end of $FT_update3$ seconds, the temperature T (e.g., in degrees Celsius) of the crystal is measured. In an embodiment, at step 710, if $|T - T_0| > T_2$ degrees, then the current estimate for $c3$ is updated at step 720.

[0078] In an embodiment, at step 720, given the most recent values of $c0$, $c1$, and $c2$, candidate values of $c3$ may be assessed to determine the best $c3$ for the measured frequency and temperature, according to some optimality criteria. Once a best $c3$ is determined, it may be IIR filtered with a previous estimate of $c3$.

[0079] At step 730, $n3$ is compared to a variable $maxIterations3$. If $n3$ has reached $maxIterations0$, then the state machine proceeds to the next state. If $n3$ has not reached $maxIterations3$, then the state returns to step 700.

[0080] In alternative embodiments of the present disclosure, other criteria may be used to determine when the state machine proceeds from one state to the next state. For example, instead of transitioning to the next state only after a predetermined number of iterations, as shown in FIGs 5, 6, and 7, the state machine may transition to the next state upon detecting little or no change in the coefficient to be updated. In an embodiment, for example, the state machine may transition from FIELD0 to FIELD1 if $|c0[n0] - c0[n0-1]| < \delta$, where δ has a suitably small value. Such embodiments are contemplated to be within the scope of the present disclosure.

[0081] In one or more exemplary embodiments, the functions described may be implemented in hardware, software, firmware, or any combination thereof. If implemented in software, the functions may be stored on or transmitted over as one or more instructions or code on a computer-readable medium. Computer-readable media includes both computer storage media and communication media including any medium that facilitates transfer of a computer program from one place to another. A storage media may be any available media that can be accessed by a computer. By way of example, and not limitation, such computer-readable media can comprise RAM, ROM, EEPROM, CD-ROM or other optical disk storage, magnetic disk storage or other magnetic storage devices, or any other medium that can be used to carry or store desired program code in the form of instructions or data structures and that can be accessed by a computer. Also, any connection is properly termed a computer-readable medium. For example, if the software is transmitted from a website, server, or other remote source using a coaxial cable, fiber optic cable, twisted pair, digital subscriber line (DSL), or wireless technologies such as infrared, radio, and microwave, then the coaxial cable, fiber optic cable, twisted pair, DSL, or wireless technologies such as infrared, radio, and microwave are included in the definition of medium. Disk and disc, as used herein, includes compact disc (CD), laser disc, optical disc, digital versatile disc (DVD), floppy disk and blu-ray disc where disks usually reproduce data magnetically, while discs reproduce data optically with lasers. Combinations of the above should also be included within the scope of computer-readable media.

[0082] A number of aspects and examples have been described. However, various modifications to these examples are possible, and the principles presented herein may be applied to other aspects as well. These and other aspects are within the scope of the following claims.

CLAIMS:

1. A method for computing coefficients for use in a polynomial approximation of a crystal oscillator frequency, the polynomial comprising a term c_0' and a coefficient c_1' times a measured temperature T of the crystal oscillator, the method comprising:
 - measuring a first temperature T_1 and a corresponding oscillator frequency $F_m(T_1)$;
 - measuring a second temperature T_2 and a corresponding oscillator frequency $F_m(T_2)$;
 - computing the coefficient c_0' based on $F_m(T_1)$; and
 - computing the coefficient c_1' based on T_1 , T_2 , $F_m(T_1)$, and $F_m(T_2)$.
2. The method of claim 1, the computing the coefficient c_0' comprising taking the difference between $F_m(T_1)$ and an initial term $F_{init}(T_1)$.
3. The method of claim 2, the initial term $F_{init}(T_1)$ comprising a term $c_{0_{init}}$ and a coefficient $c_{1_{init}}$ times T_1 .
4. The method of claim 1, the computing the coefficient c_1' comprising dividing the difference between $F_m(T_2)$ and $F_m(T_1)$ by the difference between T_2 and T_1 .
5. The method of claim 4, wherein the difference between T_1 and T_2 is at least one degree Celsius.
6. The method of claim 4, further comprising turning on a heat source after measuring T_1 and before measuring T_2 .
7. The method of claim 6, wherein the heat source is a power amplifier.
8. The method of claim 1, further comprising computing multiple estimates of c_0' and c_1' .

9. The method of claim 8, further comprising averaging together the multiple estimates of c_0' and c_1' .
10. The method of claim 8, further comprising updating estimates of c_0' and c_1' using an infinite impulse response (IIR) filter.
11. The method of claim 4, the polynomial further comprising a coefficient c_2' times a second-order function of T and a coefficient c_3' times a third-order function of T , the method further comprising:
 computing the coefficients c_2' and c_3' based on c_1' .
12. The method of claim 11, the computing the coefficient c_2' comprising multiplying c_1' by a term $m_{c_2'}$.
13. The method of claim 11, the computing the coefficient c_3' comprising multiplying c_1' by a term $m_{c_3'}$.
14. The method of claim 13, further comprising updating the term c_0' by taking the difference between $F_m(T_1)$ and $F'(T_1)$, wherein $F'(T_1)$ comprises the pre-updated term c_0' , and the computed coefficients c_1' , c_2' , and c_3' .
15. The method of claim 13, further comprising computing multiple estimates of c_0' , c_1' , c_2' , and c_3' .
16. The method of claim 15, further comprising averaging together the multiple estimates of c_0' , c_1' , c_2' , and c_3' .
17. The method of claim 15, further comprising updating estimates of c_0' , c_1' , c_2' , and c_3' using an infinite impulse response (IIR) filter.
18. The method of claim 15, further comprising updating estimates of c_0' , c_1' , c_2' , and c_3' by minimizing a mean-squared error between: 1) a frequency estimate based on candidate estimates of c_0' , c_1' , and 2) the measured frequency $F_m(T_1)$.

19. The method of claim 18, the frequency estimate based on candidate estimates of $c0'$, $c1'$ utilizing estimates for $c2'$ and $c3'$ linearly related to the candidate estimates of $c0'$ and $c1'$.

20. The method of claim 1, wherein the computing the estimates of $c0'$ and $c1'$ is done at a factory.

21. A method for computing coefficients for use in a polynomial approximation of a crystal oscillator frequency, the polynomial comprising a term $c0'$ and a coefficient $c1'$ times a measured temperature T of the crystal oscillator, the method comprising:

entering a state FIELD0, operations in the state FIELD0 comprising computing the coefficient $c0'$ if the measured temperature T is within a first range of temperatures; and

entering a state FIELD1, operations in the state FIELD1 comprising computing the coefficient $c1'$ if the measured temperature T is within a second range of temperatures.

22. The method of claim 21, the computing the coefficient $c0'$ comprising:

taking a difference between a measured frequency f_m and a calculated frequency f_{cal} to generate a first difference term, wherein f_{cal} is calculated from a previous estimate of the coefficient $c0'$ and the measured temperature T .

23. The method of claim 22, the computing the coefficient $c0'$ further comprising:

weighting a difference between the first difference term and a previous estimate of the coefficient $c0'$ by a weighting constant; and

adding the weighted difference to the previous estimate of $c0'$.

24. The method of claim 23, the computing the coefficient $c1'$ comprising:

measuring temperatures $T2$ and $T1$, and corresponding frequencies $F_m(T2)$ and $F_m(T1)$;

dividing the difference between $F_m(T2)$ and $F_m(T1)$ by the difference between $T2$ and $T1$ to generate a first quotient;

weighting the first quotient by a weighting constant; and
adding the weighted quotient to the previous estimate of $c1'$.

25. The method of claim 24, operations in the state FIELD0 further comprising waiting for a first predetermined time period before checking if the measured temperature T is within the first range of temperatures, operations in the state FIELD1 further comprising waiting for a second predetermined time period before checking if the measured temperature T is within the second range of temperatures.

26. The method of claim 25, further comprising transitioning from FIELD0 to FIELD1 if $c0'$ has been computed a first predetermined number of times in FIELD0.

27. The method of claim 25, further comprising transitioning from FIELD0 to FIELD1 if the difference between a current estimate of $c0'$ and a previous estimate of $c0'$ is less than a predetermined value.

28. The method of claim 25, further comprising transitioning from FIELD0 back to FIELD1 if a predetermined condition is met.

29. The method of claim 25, further comprising entering a state FIELD3, operations in the state FIELD3 comprising computing the coefficient $c3'$ if the measured temperature T is within a fourth range of temperatures, operations in the state FIELD3 further comprising waiting for a fourth predetermined time period before checking if the measured temperature T is within the fourth range of temperatures.

30. The method of claim 29, the computing the coefficient $c3'$ comprising determining an estimate of $c3'$ that minimizes a mean-squared error between: 1) a frequency estimate based on the updated values of $c0$, $c1$, $c2$, and a candidate estimate of $c3'$, and 2) the measured frequency $F_m(T1)$.

31. The method of claim 30, further comprising IIR filtering the estimate of $c3'$ with a previous estimate of $c3'$.

32. The method of claim 31, further comprising transitioning from FIELD1 to FIELD3 if $c1'$ has been computed a second predetermined number of times.
33. The method of claim 31, further comprising transitioning from FIELD1 to FIELD3 if the difference between a current estimate of $c1'$ and a previous estimate of $c1'$ is less than a predetermined value.
34. An apparatus for computing coefficients for use in a polynomial approximation of a crystal oscillator frequency, the polynomial comprising a term $c0'$ and a coefficient $c1'$ times a measured temperature T of the crystal oscillator, the apparatus comprising:
a temperature measurement unit for measuring a first temperature $T1$ and a second temperature $T2$;
a frequency measurement unit for measuring corresponding oscillator frequencies $Fm(T1)$ and $Fm(T2)$; and
a computing module for computing the coefficient $c0'$ based on $Fm(T1)$, and for computing the coefficient $c1'$ based on $T1$, $T2$, $Fm(T1)$, and $Fm(T2)$.
35. The apparatus of claim 34, the computing module computing the coefficient $c0'$ by taking the difference between $Fm(T1)$ and an initial term $F_{init}(T1)$.
36. The apparatus of claim 34, the computing module computing the coefficient $c1'$ by dividing the difference between $Fm(T2)$ and $Fm(T1)$ by the difference between $T2$ and $T1$.
37. The apparatus of claim 34, the polynomial further comprising a coefficient $c2'$ times a second-order function of T , the computing module further computing the coefficient $c2'$ by performing a linear operation on the computed coefficient $c1'$.
38. The apparatus of claim 37, the polynomial further comprising a coefficient $c3'$ times a third-order function of T , the computing module further computing the coefficient $c3'$ by performing a linear operation on the computed coefficient $c1'$.

39. An apparatus for computing coefficients for use in a polynomial approximation of a crystal oscillator frequency, the polynomial comprising a term c_0' and a coefficient c_1' times a measured temperature T of the crystal oscillator, the apparatus comprising:

- means for measuring a first temperature T_1 and a second temperature T_2 ;
- means for measuring corresponding oscillator frequencies $F_m(T_1)$ and $F_m(T_2)$;
- means for computing the coefficient c_0' based on $F_m(T_1)$, and for computing the coefficient c_1' based on T_1 , T_2 , $F_m(T_1)$, and $F_m(T_2)$.

40. A computer program product for computing coefficients for use in a polynomial approximation of a crystal oscillator frequency, the polynomial comprising a term c_0' and a coefficient c_1' times a measured temperature T of the crystal oscillator, the product comprising:

- computer-readable medium comprising:
 - code for causing a computer to measure a first temperature T_1 and a corresponding oscillator frequency $F_m(T_1)$;
 - code for causing a computer to measure a second temperature T_2 and a corresponding oscillator frequency $F_m(T_2)$;
 - code for causing a computer to compute the coefficient c_0' based on $F_m(T_1)$;
 - code for causing a computer to compute the coefficient c_1' based on T_1 , T_2 , $F_m(T_1)$, and $F_m(T_2)$.

41. An apparatus for computing coefficients for use in a polynomial approximation of a crystal oscillator frequency, the polynomial comprising a term c_0' and a coefficient c_1' times a measured temperature T of the crystal oscillator, the apparatus comprising:

- means for entering a state FIELD0, operations in the state FIELD0 comprising computing the coefficient c_0' if the measured temperature T is within a first range of temperatures; and

- means for entering a state FIELD1, operations in the state FIELD1 comprising computing the coefficient c_1' if the measured temperature T is within a second range of temperatures.

42. The apparatus of claim 41, the computing the coefficient c_0' comprising taking a difference between a measured frequency f_m and a calculated frequency f_{cal} to generate

a first difference term, wherein f_{cal} is calculated from a previous estimate of the coefficient c_0' and the measured temperature T .

43. A computer program product for computing coefficients for use in a polynomial approximation of a crystal oscillator frequency, the polynomial comprising a term c_0' and a coefficient c_1' times a measured temperature T of the crystal oscillator, the product comprising:

computer-readable medium comprising:

code for causing a computer to enter a state FIELD0, operations in the state FIELD0 comprising computing the coefficient c_0' if the measured temperature T is within a first range of temperatures; and

code for causing a computer to enter a state FIELD1, operations in the state FIELD1 comprising computing the coefficient c_1' if the measured temperature T is within a second range of temperatures.

44. The computer program product of claim 43, the code for causing a computer to compute the coefficient c_0' comprising code for causing a computer to take a difference between a measured frequency f_m and a calculated frequency f_{cal} to generate a first difference term, wherein f_{cal} is calculated from a previous estimate of the coefficient c_0' and the measured temperature T .

45. The computer program product of claim 43, the code for causing a computer to compute the coefficient c_0' further comprising:

code for causing a computer to weight a difference between the first difference term and a previous estimate of the coefficient c_0' by a weighting constant; and

code for causing a computer to add the weighted difference to the previous estimate of c_0' .

46. The computer program product of claim 45, the code for causing a computer to compute the coefficient c_1' comprising:

code for causing a computer to measure temperatures T_2 and T_1 , and corresponding frequencies $F_m(T_2)$ and $F_m(T_1)$;

code for causing a computer to divide the difference between $F_m(T_2)$ and $F_m(T_1)$ by the difference between T_2 and T_1 to generate a first quotient;
code for causing a computer to weight the first quotient by a weighting constant;
and
code for causing a computer to add the weighted quotient to the previous estimate of c_1' .

47. The computer program product of claim 46, operations in the state FIELD0 further comprising waiting for a first predetermined time period before checking if the measured temperature T is within the first range of temperatures, operations in the state FIELD1 further comprising waiting for a second predetermined time period before checking if the measured temperature T is within the second range of temperatures.

48. The computer program product of claim 47, the computer-readable medium further comprising code for causing a computer to transition from FIELD0 to FIELD1 if c_0' has been computed a first predetermined number of times in FIELD0.

49. The computer program product of claim 48, the computer-readable medium further comprising code for causing a computer to enter a state FIELD3, operations in the state FIELD3 comprising computing the coefficient c_3' if the measured temperature T is within a fourth range of temperatures, operations in the state FIELD3 further comprising waiting for a fourth predetermined time period before checking if the measured temperature T is within the fourth range of temperatures.

50. The computer program product of claim 49, the computer-readable medium further comprising code for causing a computer to transition from FIELD1 to FIELD3 if c_1' has been computed a second predetermined number of times.

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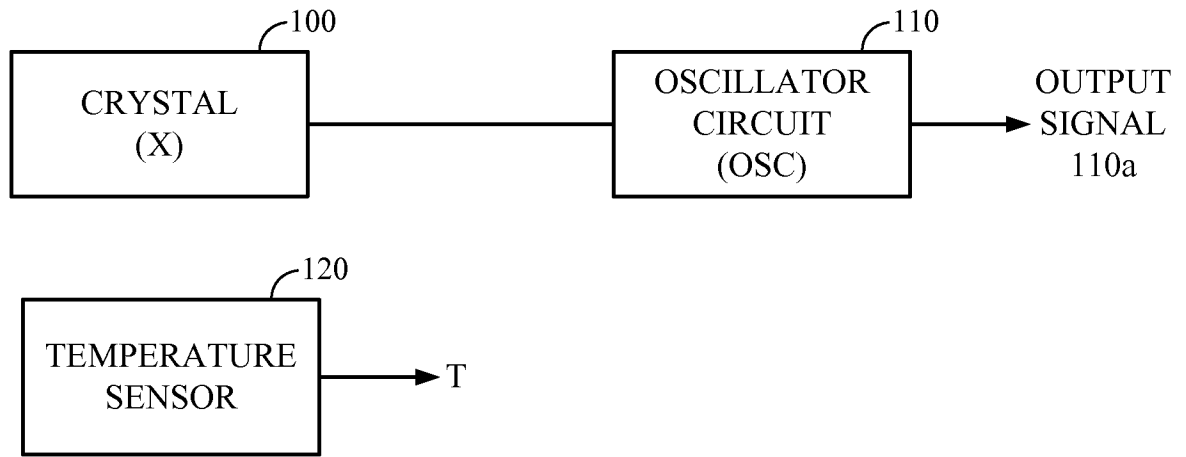


FIG. 1

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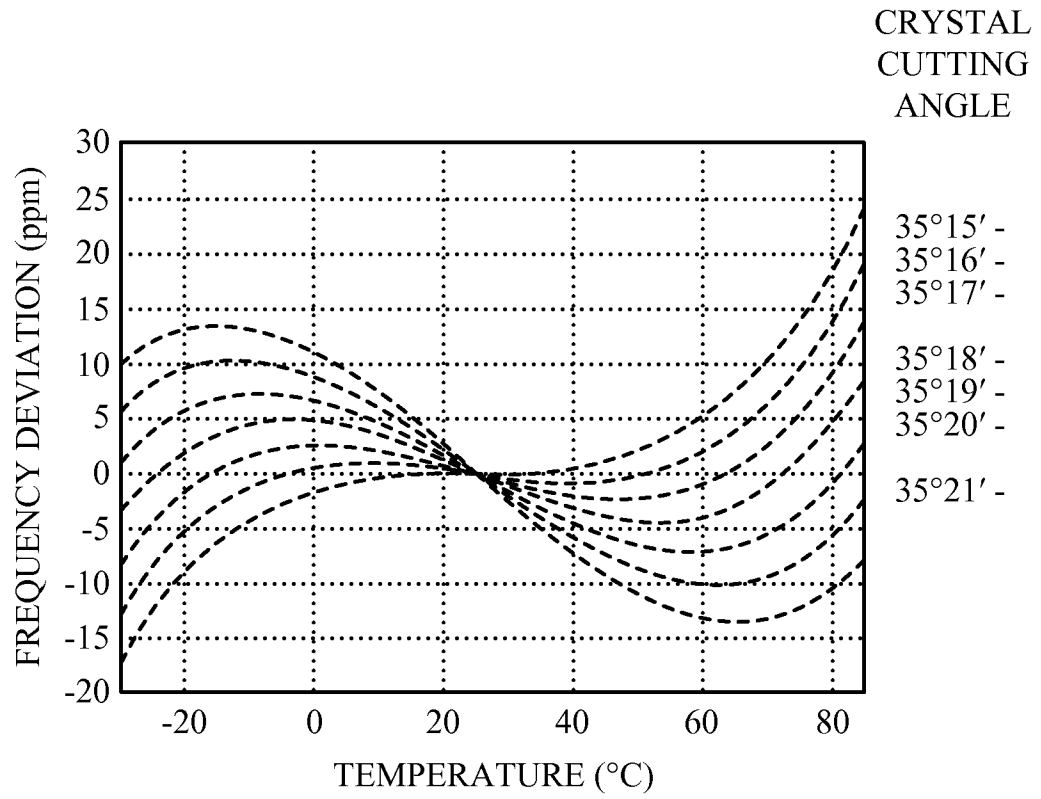


FIG. 1A

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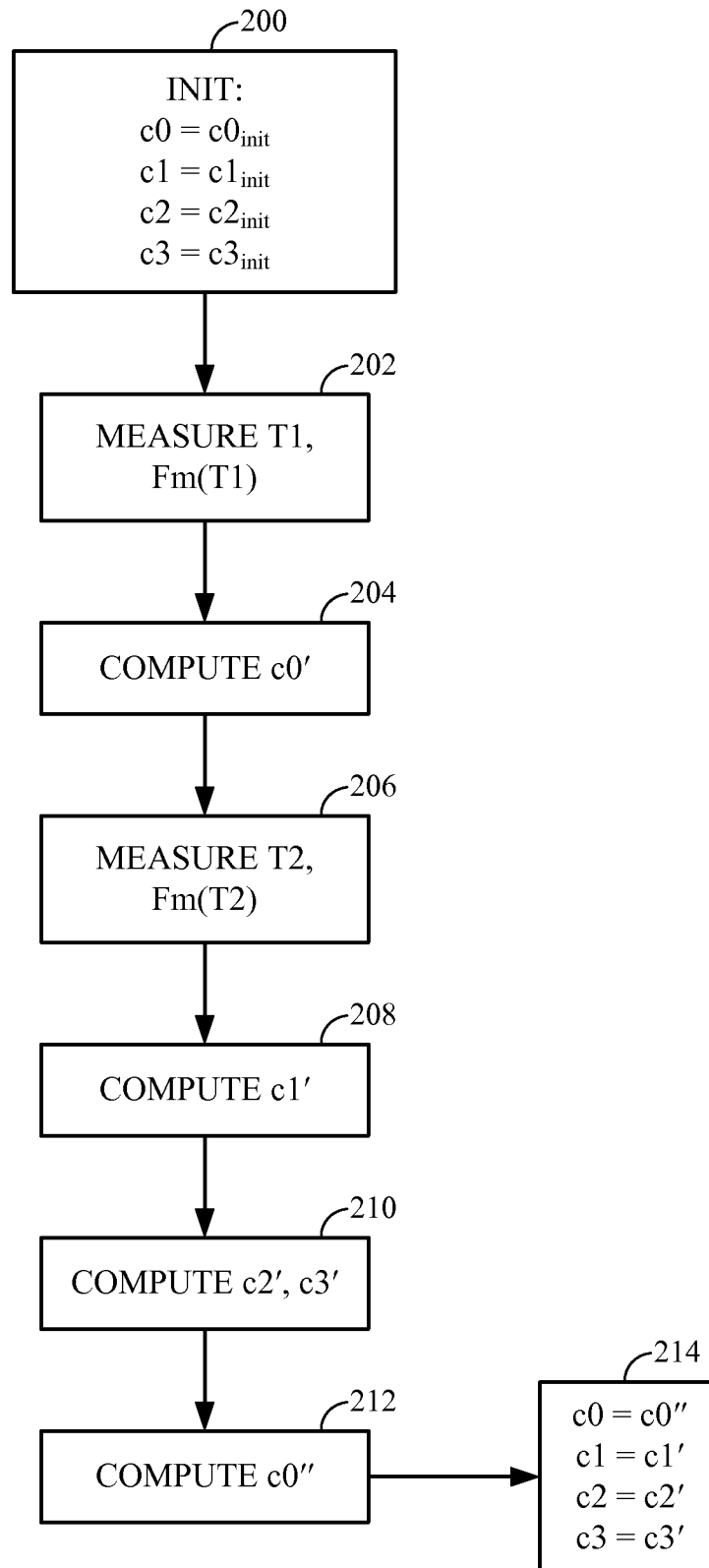


FIG. 2

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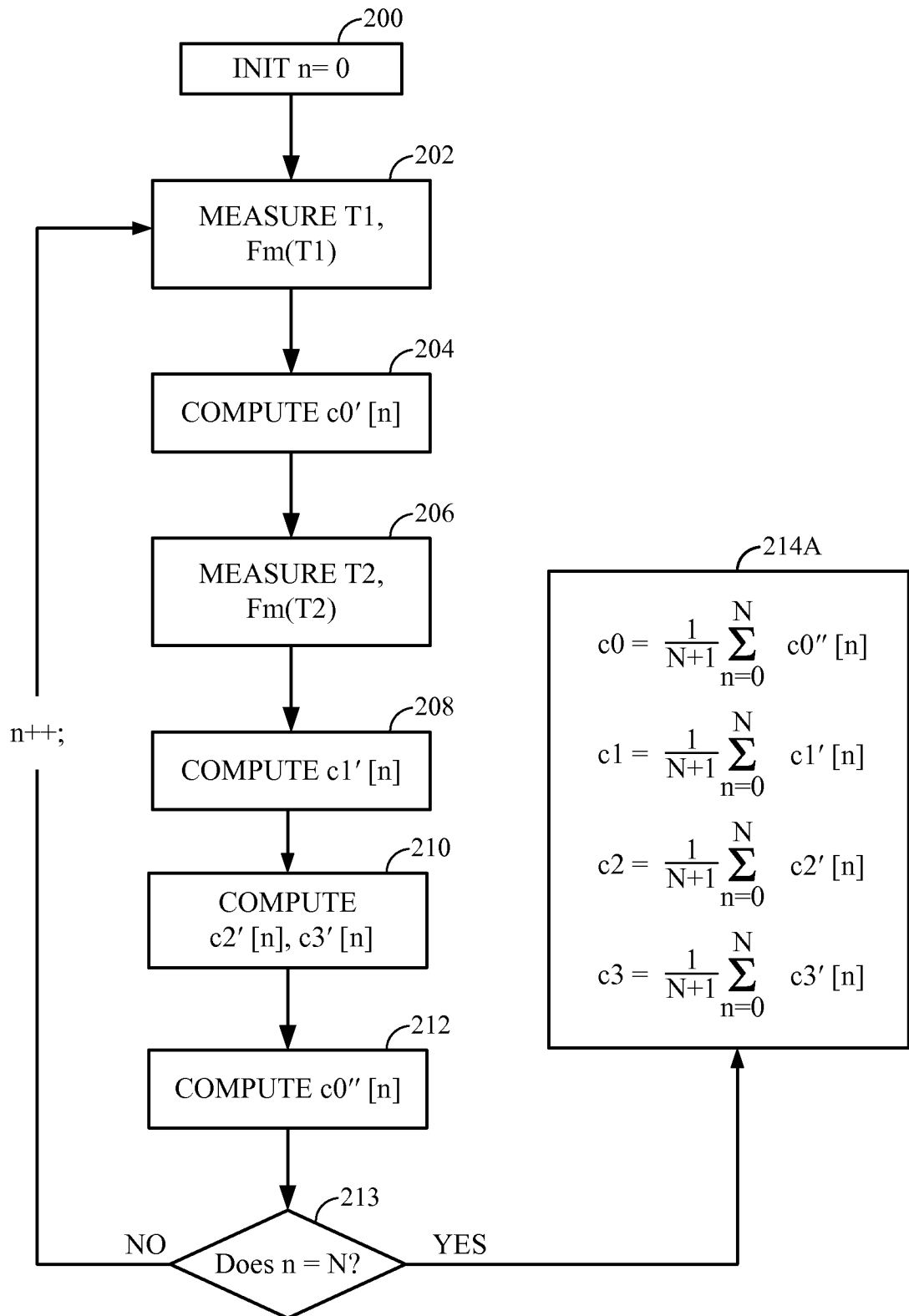


FIG. 2A

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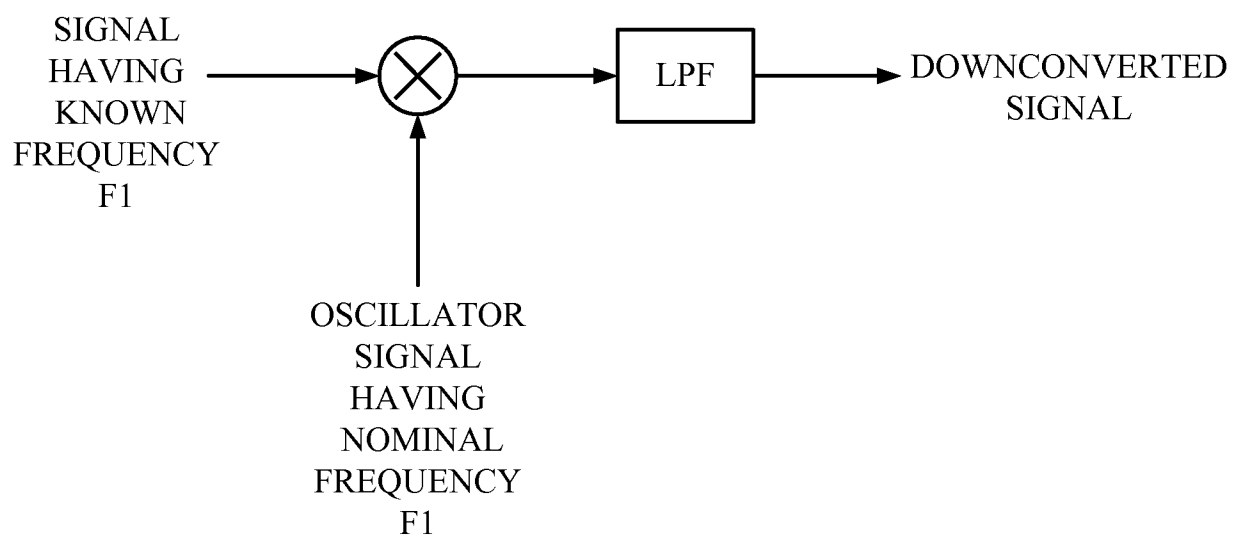


FIG. 2B

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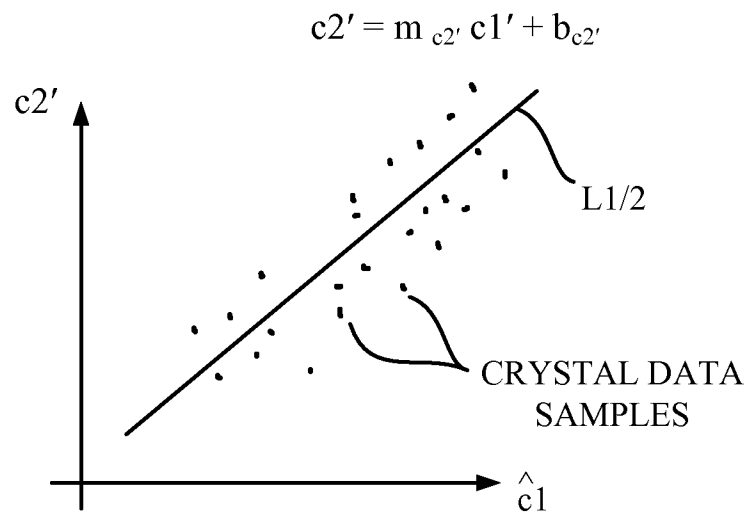


FIG. 3A

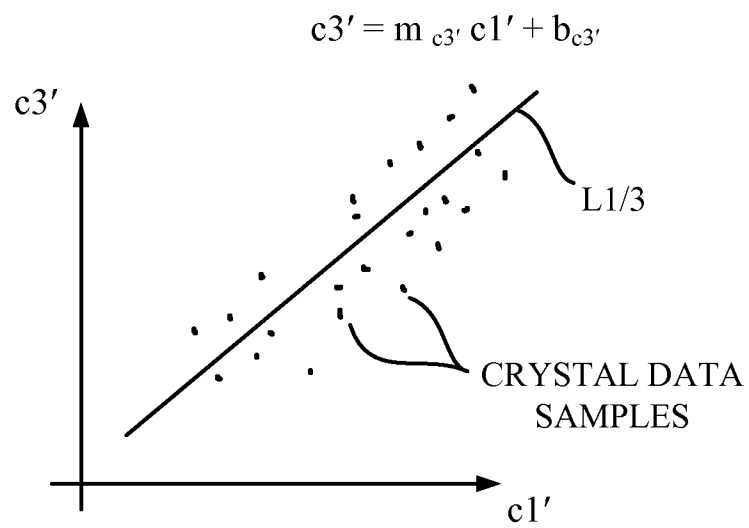


FIG. 3B

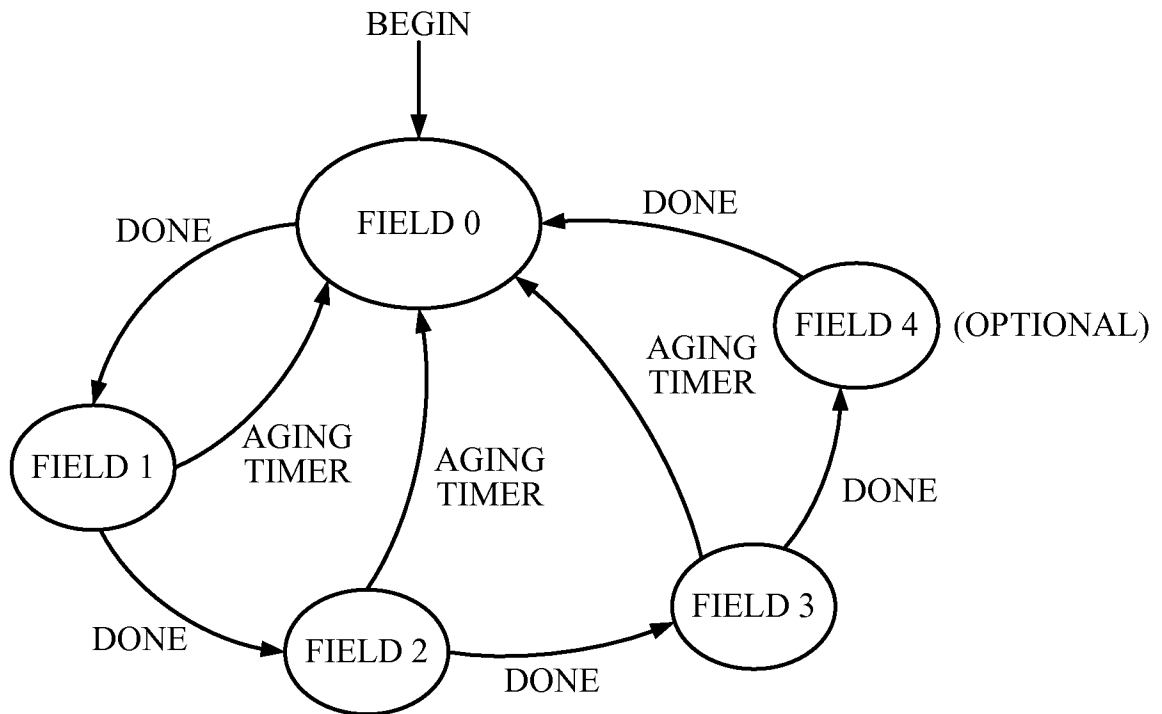


FIG. 4

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STATE FIELD 0

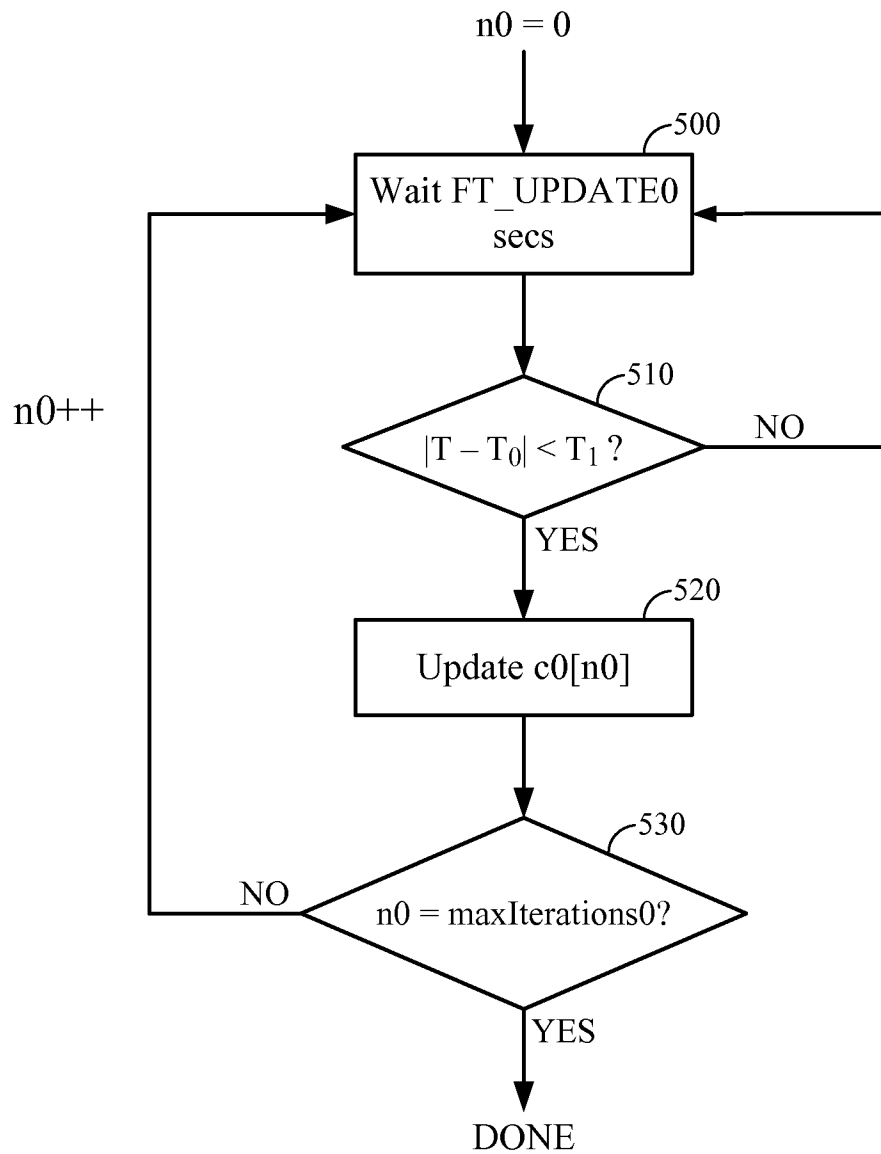


FIG. 5

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STATE FIELD 1

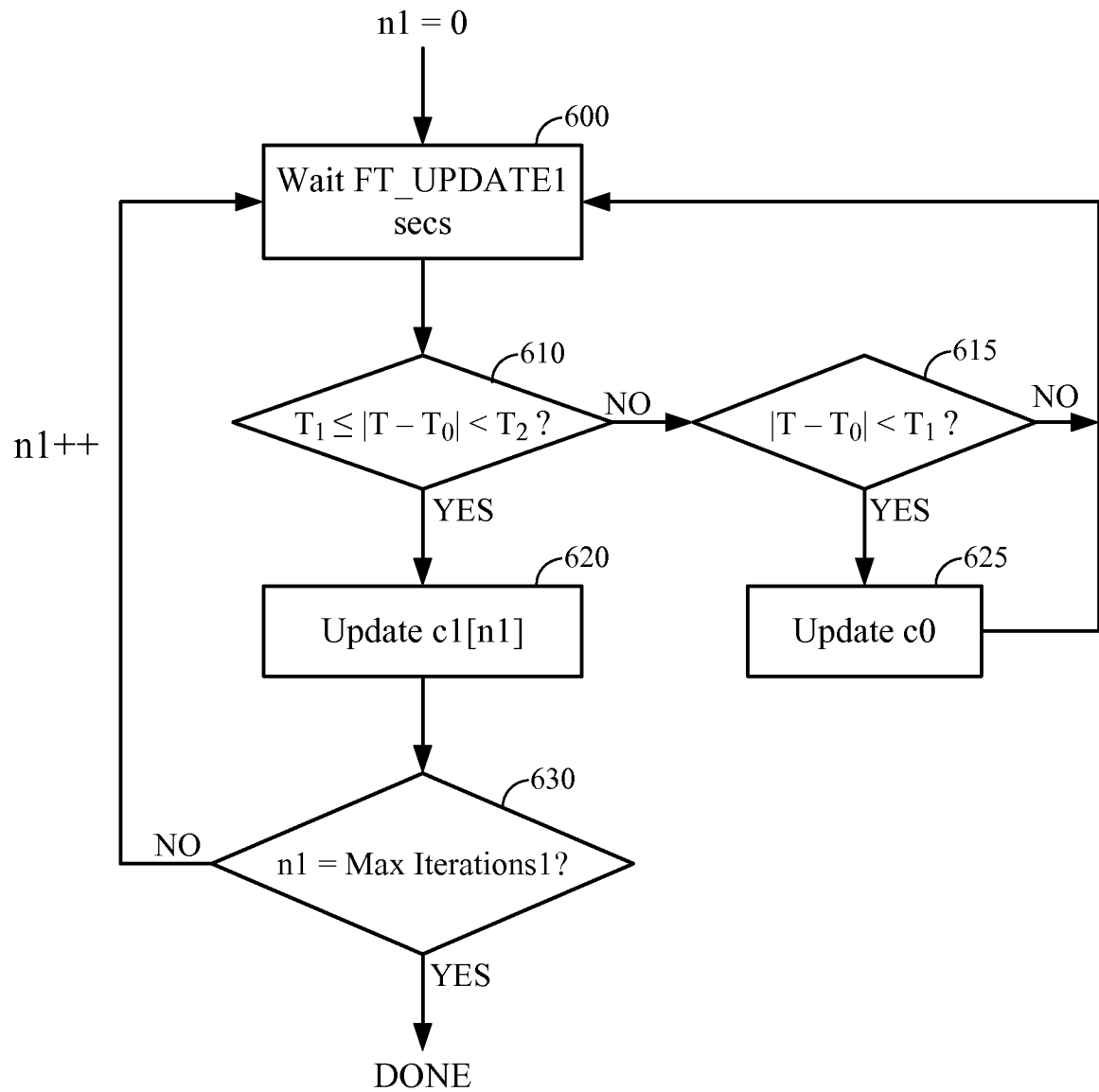
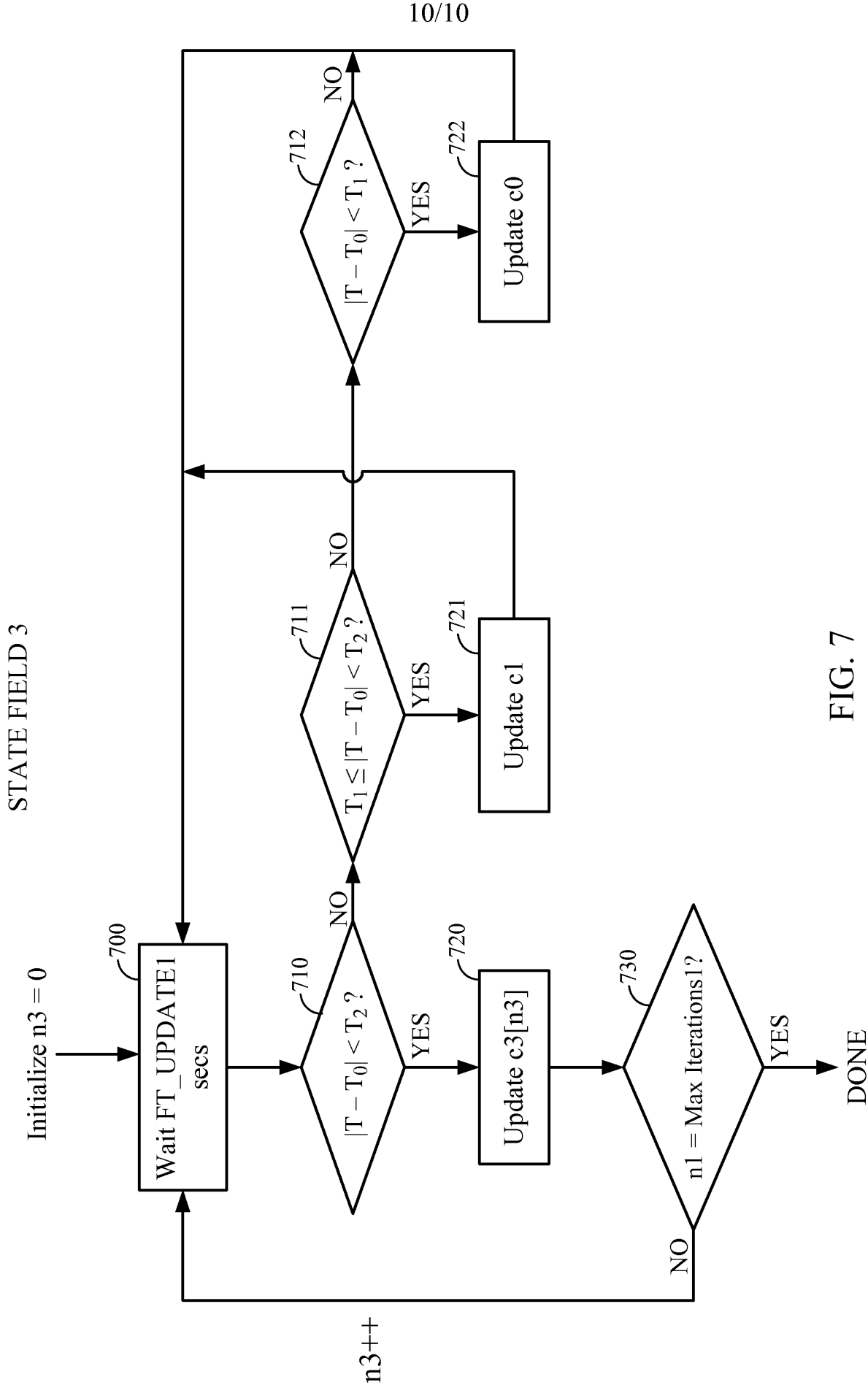


FIG. 6



INTERNATIONAL SEARCH REPORT

International application No
PCT/US2009/032503

A. CLASSIFICATION OF SUBJECT MATTER
INV. G06F17/50

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G06F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	PERETTO L ET AL: "A System for the Measurement of the Temperature Dependence Performances of Quartz Oscillators: a Study of the Analytical Model of the Failure Rate" INSTRUMENTATION AND MEASUREMENT TECHNOLOGY CONFERENCE PROCEEDINGS, 200 7 IEEE, IEEE, PI, 1 May 2007 (2007-05-01), pages 1-6, XP031182227 ISBN: 978-1-4244-0588-6 the whole document, in particular Fig. 1 "The Test and Measurement System" and Fig. 4 ----- -/--	1-50

☒ Further documents are listed in the continuation of Box C.

☐ See patent family annex.

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- *T* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
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- *Y* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
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Date of the actual completion of the international search

19 May 2009

Date of mailing of the international search report

03/06/2009

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Authorized officer

Lerbinger, Klaus

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2009/032503

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	BALLATO A: "Frequency-temperature-load capacitance behavior of resonators for TCXO application" IEEE TRANSACTIONS ON SONICS AND ULTRASONICS USA, vol. SU-25, no. 4, July 1978 (1978-07), pages 185-191, XP002528763 ISSN: 0018-9537 cited in the application the whole document, in particular chapter "Frequency-Temperature Behavior" -----	1-50