**Proceedings of the 2003 IEEE International Frequency Control Symposium and PDA Exhibition
Jointly with the 17th European Frequency and Time Forum**

A NOVEL APPROACH TO IMPROVING THE STABILITY OF TCVCXO TEMPERATURE PERFORMANCE

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Abstract - **The output frequency of a temperature compensated voltage controlled oscillator is determined by the sum of an internally generated compensation voltage and an externally applied adjustment voltage. Without correction, non-linearities in the frequency vs voltage characteristic of the VCXO result in the frequency vs temperature characteristic of the device being dependent on the adjustment voltage. This is known as 'trim skew'. Additionally, the slope of the frequency vs voltage curve will be a function of temperature due to the temperature dependence of the crystal C_1 and of the varactor diode, limiting the temperature stability achievable.**

Both these effects are minimised in C-MAC's latest high performance TCXO ASIC, code named 'Pluto'. Pluto has an additional circuit block inserted before the VCXO. The weighted sum of the compensation and adjustment voltages form the input to this novel circuit block, while the output is the voltage applied to the varactor , adjusting the frequency of the VCXO. As described in patent application EP1209812/US2002060597, the non-linear transfer function of the block can be digitally programmed to accurately compensate for the non-linearity of the VCXO's frequency adjustment. A temperature sensor provides an additional input to the block. This is used to control the overall gain of the circuit in such a way as to correct for the temperature dependence of the crystal C1 and the varactor.

The result is that a highly linear VCXO is achieved with constant voltage sensitivity over the temperature range. This in turn allows exceptional frequency vs temperature stability to be achieved over the whole adjustment voltage range. The digital control of the multiplying DACs used in the linearisation allows individual settings to be made, giving optimum results for each oscillator.
Keywords: **Linearity, TCXO, stability, trim-skew**

I. INTRODUCTION

The typical frequency adjustment characteristics of an oscillator containing a varactor as a tuning element exhibit non-linear performance. An ideal abrupt varactor follows a capacitance – voltage curve given by (1), where *Cnom* is the nominal capacitance of the varactor with zero volts applied, V_{BI} is the temperature dependant built in voltage and *V* is the DC voltage applied. The frequency deviation of the oscillator from series resonance, *D* (ppm) is given in (2) where *C1* is the temperature dependant motional capacitance of the crystal, *C0* is the effective parallel capacitance and *CL* is the capacitance of the oscillator loop.

$$C(V) = \frac{Cnom}{\left(\frac{V}{V_{BI}}+1\right)^{0.5}} \tag{1}$$

$$D(CL) = \frac{C1\times10^{6}}{2\times(C0+CL)} \tag{2}$$

Combining equation (1) with (2) and including *Cosc*, the oscillator capacitance, in series with the varactor, gives the oscillator frequency deviation as a function of control voltage to be

$$D(V) = \frac{C1\times10^{6}}{2\times\left(C0+\frac{1}{\frac{1}{Cosc}+\frac{(\frac{V}{V_{BI}}+1)^{0.5}}{Cnom}}\right)} \tag{3}$$

This gives the characteristic frequency adjustment curve, normalised to a control voltage of 1.4V as shown in Fig 1.

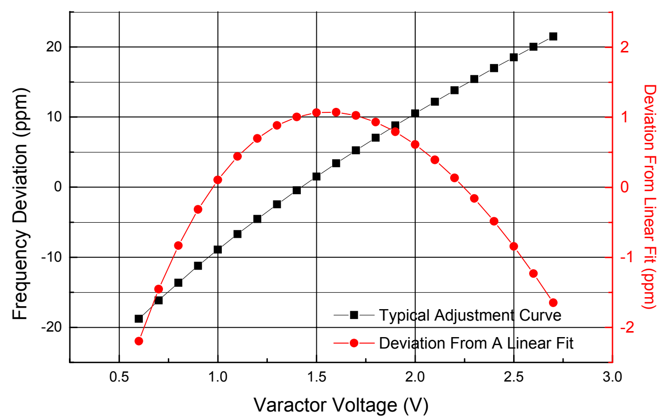

Fig 1: Typical Oscillator Sensitivity Curve

Improvement of Temperature Compensation

One of the limitations of temperature compensation using a digitally set analogue system is the order of the polynomial needed to generate an exact voltage to correct the temperature performance of the crystal resonator. The temperature behaviour of an AT cut crystal may be modelled approximately as having a deviation of the series resonant frequency shown in (4),

$$D(T) = a(T-T0)+c(T-T0)^{3} \tag{4}$$

where *T* is the temperature, *T0* is the inflection temperature of the resonator and coefficients *a* and *c* are the coefficients of the polynomials to fit the resonator's behaviour. Applying a voltage to the varactor in the oscillator loop alters the frequency, Fig 1. Conversely, the voltage to give a frequency deviation of the oscillator may be (third-order) approximated as in (5),

$$V(D) \;=\; V_0 + eD + fD^2 + gD^3 \tag{5}$$

where the coefficients *e,f* and *g* are the levels of each order and *V0* is the voltage for zero frequency deviation. If a correction voltage is applied to the varactor, aimed at compensating the temperature effects of the crystal resonator, the applied voltage, V(T) is arrived at by substituting -D(T) into V(D) as in (6)

$$V(T) \;=\; V(-D(T)) \tag{6}$$

Expanding gives (7),

$$\begin{aligned} V(T) \;=\; & V_0 - e\left[c(T-T0)^3 + a(T-T0)\right] - \\ & f\left[c(T-T0)^3 + a(T-T0)\right]^2 - \\ & g\left[c(T-T0)^3 + a(T-T0)\right]^3 \end{aligned} \tag{7}$$

which clearly indicates the higher orders to be present. The cubic term in (4) and the quadratic term in (5) dominate, giving a significant content of fourth to sixth order terms; although orders up to and including the ninth will be present. Significant fourth order is added by the temperature dependence of pulling sensitivity.

The lower the coefficients of *f* and *g,* the non-linear components of the control voltage to frequency transfer function, the smaller are the levels of the higher orders that are needed to achieve a well compensated device.

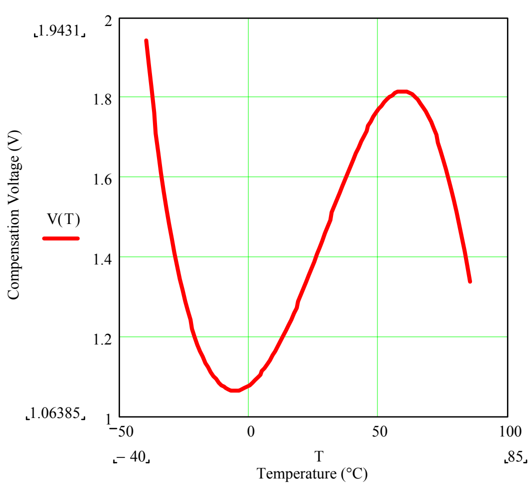

Fig 2 : Ideal Temperature Compensation Voltage

Order	Voltage Coefficients
0	1.4942
1	0.0489
2	0.1390
3	-0.3442
4	-1.265E-3
5	-7.0531E-3
6	8.6025E-3

Table 1 :Chebychev Coefficients for Ideal Compensation

Fig 2 shows a theoretically ideal voltage/temperature requirement to compensate an AT crystal resonator where the controlling voltage function is applied to the oscillator via a typical varactor. Mean sensitivity is 20ppm/volt. Curve fitting a sixth order Chebychev (mini-max) polynomial to the data in Fig 2 for the control voltage gives coefficients shown Table 1. Subsequent truncation from the full six orders down to third, fourth and fifth orders increases the residual voltage and frequency errors. Results are in Table 2.

Highest Order Present	Voltage Error (mV)	Frequency Error (ppm)
6	≈0	≈0
5	8.6	0.17
4	14.7	0.29
3	14.9	0.30

Table 2 : Stability Errors of Limiting the Compensation Order

"Trim-Skew"

From the data shown in Fig 1 the sensitivity of the frequency adjustment with respect to the control voltage varies with the absolute voltage level. If a control signal is generated to compensate or remove all frequency deviation as in (7) and illustrated in Fig 2, the nominal performance of the TCXO will be ideal. If the TCXO is now trimmed by altering the external control voltage, an offset is effectively added to the voltage across the varactor. With the slope of the adjustment curve varying across the range, the previously ideal voltage/temperature signal will no longer match that required to remove the frequency deviation and an error will now exist. A calculated example is shown in Fig 3. Here a perfectly compensated device is externally adjusted to change the control voltage ± 0.3 Volts from nominal, giving an adjustment of about ±6ppm and the temperature performance is recalculated. The nominal frequency control deviation is subtracted from the curves so that only the error remains.

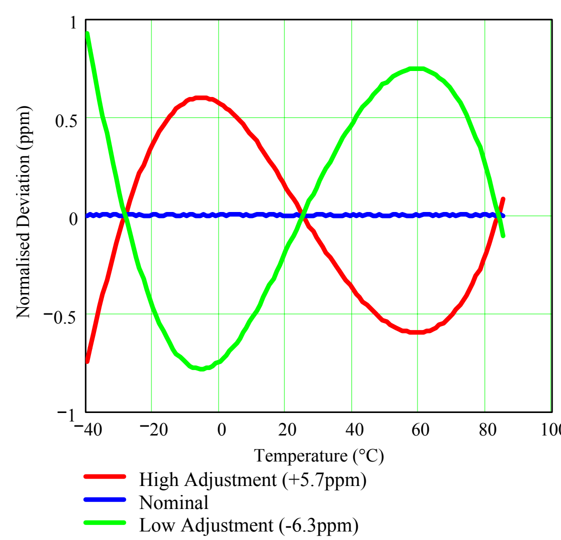

Fig 3: "Trim-Skew"

II. METHODOLOGY

The linearising block, necessary to compensate for the curve in (5) is added inside the TCXO to process the signal which comprises the sum of the temperature compensation output and the external adjustment input as shown in Fig 4. Linearising the sum requires only one linearising block and generates a linear transfer function for both inputs and ensures that minimum interaction between the two is achieved.

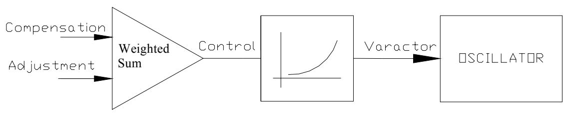

Fig 4: Addition of "Pre-Distortion" to a TCVCXO

The method chosen to create the variable distortion is shown in Fig 5 and this implementation is the simplest practical arrangement proposed in the patent [1]. Extreme care must be taken with the ASIC design and layout to ensure that process parameters, device matching, thermal and mechanical effects are compensated or minimised wherever possible, as this is a sensitive analogue circuit.

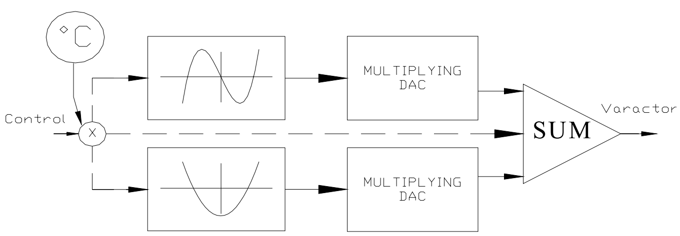

Fig 5 : Method to Generate Non-Linear Function

The control signal to the block is split into weighted portions. The individual signals are scaled by multiplying DACs to provide correction for a typical range of varactor tuning circuits. The individually weighted signals are passed through different distortion functions; in this case a third order Chebychev power series in the form of

$$\begin{aligned} T_0(x) &= 1 \\ T_1(x) &= x \\ T_N(x) &= 2x \times T_{N-1}(x) - T_{N-2}(x) \end{aligned} \tag{8}$$

Fig 5 shows the current implementation, where a programmable level of second and third order distortion is summed with the original signal. The amount of each distorted order is specified by the digital control word of the associated multiplying DAC. DAC settings are capable of changing sign so that each order can be added in either polarity, allowing flexibility of applying the circuit to off chip varactors. An additional parameter of temperature is added to the input amplifier, scaled by a digital control word and is used to control the overall gain. This is adjusted to compensate for the lumped temperature coefficients of the oscillator, crystal and varactor.

For TCXO device manufacture, based upon C-MAC's "Pluto" ASIC, the linearisation procedure can be carried out on an individual basis for every manufactured device by sweeping the input to the distortion block over a defined range and recording the oscillator's corresponding frequency. Initially, the reference curve is created with a pre-defined amount of distortion added, derived from the design stage. The multiplying DACs are then adjusted to known settings and subsequent pulling curves are measured. Polynomial curves are fitted to these results, to derive the coefficients of each polynomial order for each setting and hence the sensitivity of the transfer function to the DAC changes can be established. Assuming the DACs to be linear in their control, the optimum conditions for each device can be very quickly achieved. Measuring each device and generating unique values removes any issue with component tolerances.

An alternative method, used for illustration and mathematical modelling, is to produce a three-dimensional array of linearity error against independent settings of the second and third order distortion controls. Initially, expressions for the voltage distortion are derived, plotted and these are then applied to (7), generating frequency/voltage results for the DAC control settings. For each result, the non-linearity can be calculated for the frequency control curve. The available signal distortions are shown in Fig 6 and Fig 7 for calculated results of the distortion at a node inside the ASIC, before the voltage is applied to the varactor.

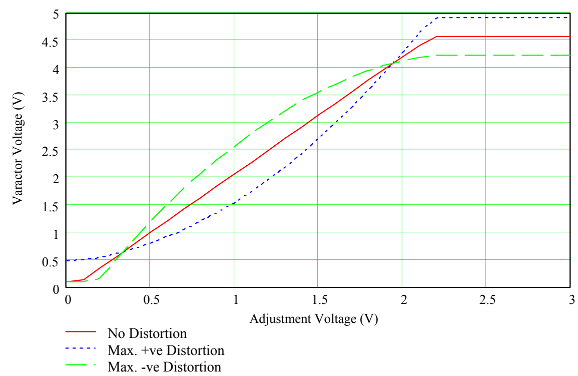

Fig 6: Second Order Distortion

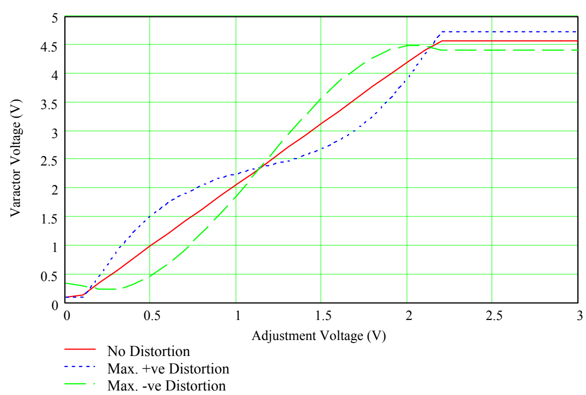

Fig 7: Third Order Distortion

A simplex technique can then be launched on the resulting array, to arrive at a value approaching the minimum distortion. For each crystal and varactor type, a unique array can be recalculated to assist with design implementation. An example ideal array is shown in Fig 8. The horizontal plane is made up from settings of the two DAC settings and the linearity error plotted vertically.

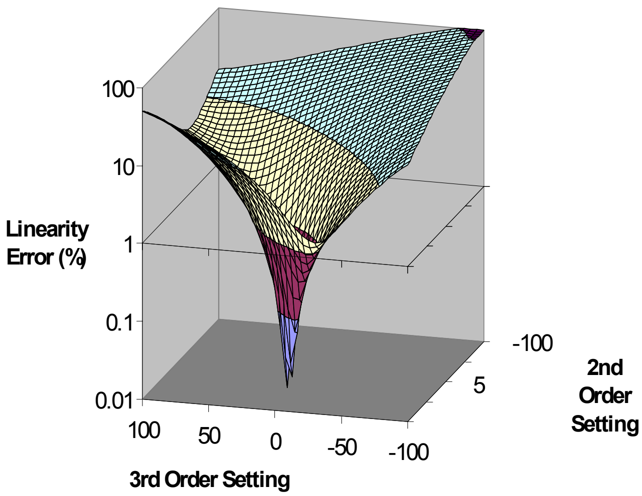

Fig 8: Linearity Error for Digital Control Settings

With the ability to correct for linear temperature coefficients, the pulling curve is initially linearised and the frequency slope is measured. The temperature of the device is changed as part of the "frequency compensation" temperature sweep and the frequency slope is measured again with minimum and maximum temperature dependant gain settings.

By recording the change in frequency slope over the given temperature difference, a digital control setting for the temperature gain input to the amplifier can now be set, resulting is a constant frequency slope over the temperature range.

III. RESULTS

The "Pluto" device is proven to operate and compensate devices from –55 to +125 degrees centigrade. The results shown below are measured results taken from C-MAC's "Pluto" 7x5 TCXO program. A –20 to +70 degrees centigrade device has been chosen, as large amounts of data are available. The device is assembled in a 7x5 HTCC package, comprising the "Pluto" ASIC, two 0402 capacitors and a 12.8 MHz strip crystal resonator. Fig 9 shows the linearity of the external customer input at 25°C and the deviation from a best linear fit. Fig 10 shows the distortion over temperature. Fig 11 displays the compensated adjustment sensitivity over temperature. Typical devices in standard production give 0.3% linearity error when calculated in accordance with MIL-PRF-55310D. The modulation bandwidth of the adjustment input is 5kHz and this is typical of devices in production.

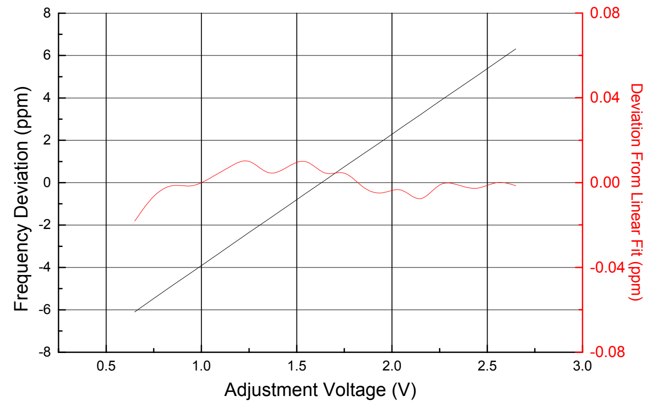

Fig 9: Adjustment Linearity

The improved performance is also noted in the overall stability of the TCXO, not only at the nominal adjustment voltage, but also over the entire range of the external adjustment signal. Fig 12 shows measured readings of a device where the nominal frequency is adjusted by over 6ppm and the corresponding frequency stability with temperature is recorded. The temperature compensation signal used in this device is a four order Chebychev arrangement (8), based upon techniques developed in C-MAC's earlier TCXO development program [2]. Not only does the nominal performance with four orders of temperature compensation exceed the previous sixth order device's but now the stability is maintained on the (linearised) device regardless of control voltage input.

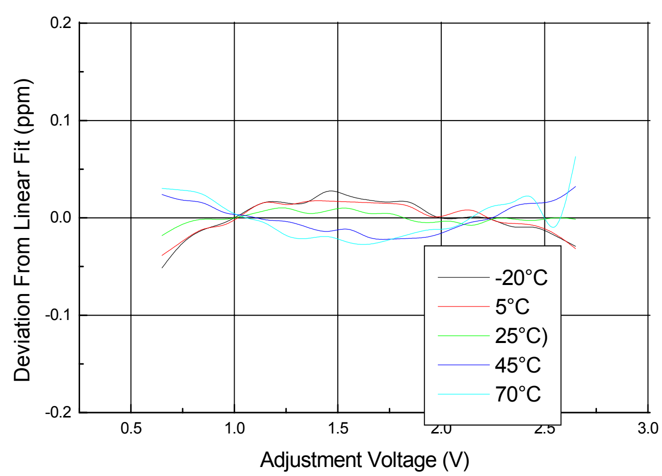

Fig 10 : Adjustment Linearity Error Over Temperature

Fig 13 shows the phase noise results of a single oscillator from a three oscillator comparison. The noise is limited by the oscillator and buffer circuitry.

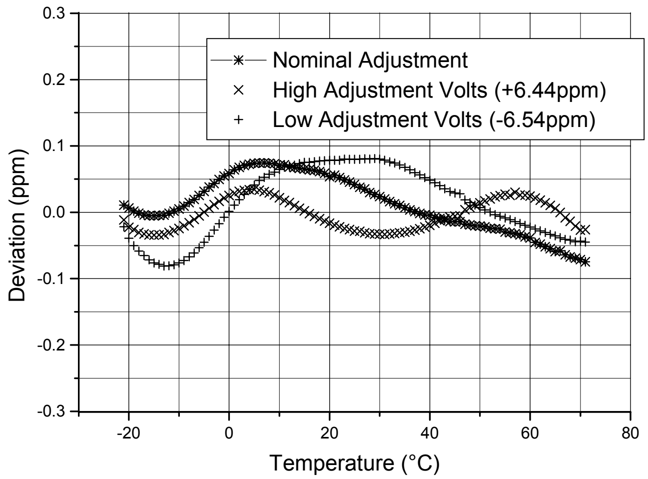

Fig 11: Variation of Adjustment Sensitivity With Temperature

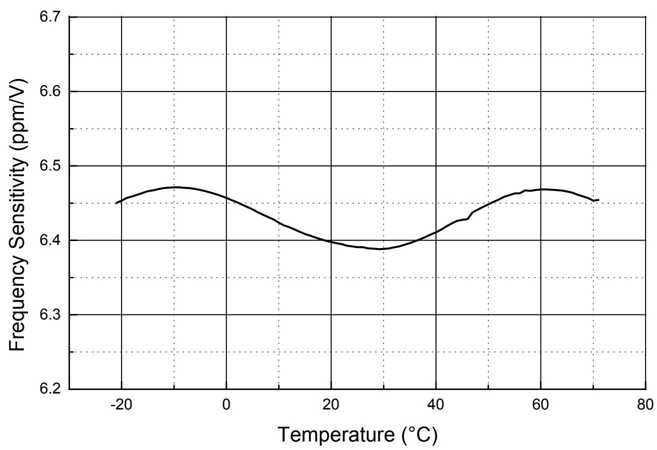

Fig 12: Temperature Performance at Adjustment Signal Extremes

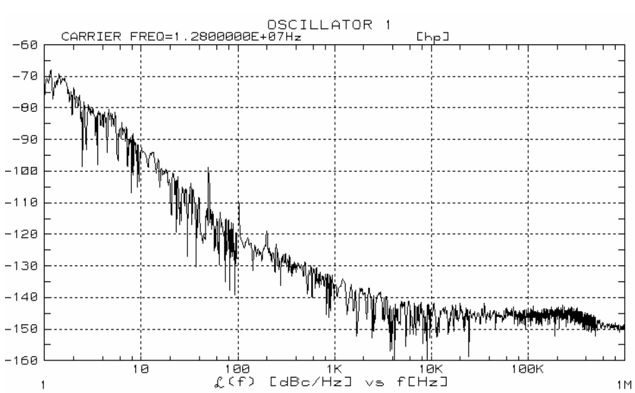

Fig 13 : Oscillator Phase Noise

IV. CONCLUSION

We have demonstrated a single ASIC practical solution, which has created a significant performance increase to the frequency stability over the temperature range by linearising the voltage to frequency control function. The performance achieved with the four temperature orders removes the necessity of a higher order device. The external control signal no longer has a large impact on the frequency stability and the transfer function of the external adjustment is highly linear and the sensitivity is reasonably constant over temperature. The distortion block does not add any significant level of noise to adversely degrade the phase noise performance of the device.

ACKNOWLEDGMENT

The staff of C-MAC Harlow, particularly Dr. N.D. Hardy, G. Trudgen and G.H.S. Rokos for practical work and experimentation and for providing information and assistance with this paper.

REFERENCES

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