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THE MICROCOMPUTER COMPENSATED CRYSTAL OSCILLATOR (MCXO)

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ABSTRACT

The MCXO uses a new technique to achieve temperature compensation without use of ovens or conventional temperature-compensating components. The crystal oscillator in the MCXO, which is free to vary with temperature, operates on two modes simultaneously -- the fundamental (f_{1c}) and the third overtone (f_{3c}). The fundamental is multiplied by 3 ($3f_{1c}$) and subtracted from f_{3c} to produce a beat frequency (f_B). This beat frequency is used as a temperature indicator to correct the frequency of the fundamental or the third overtone, either of which may be used to generate the output (f_o) of the MCXO.

Five MCXOs were delivered to the U.S. Army by FEI. Their testing showed that the units provide the following performance:

Frequency vs. temperature	5×10^{-8} over the temperature range of -55 to +85°C
Aging	1×10^{-10} per day
Input power	41 mW

The output of the MCXO is a pulse train from which pulses have been deleted under microcomputer control. The beat frequency is counted and the microcomputer, which stores the relationship between the oscillator output (f_{1c} or f_{3c}) and f_B, determines the number of pulses that must be deleted from the pulse train per unit of time.

Several advantages accrue because this method of temperature compensation does not resort to frequency pulling. In many applications, the MCXO will replace conventional temperature-compensated crystal oscillators, providing an order-of-magnitude improvement in frequency vs. temperature performance. In applications requiring low power consumption, the MCXO will replace OCXOs.

This paper presents the details of how the MCXO operates and the details of the performance of the delivered systems.

INTRODUCTION

Because of limitations related to thermal hysteresis in AT-cut crystal units, lack of precision in analog compensating networks and the trim effect, efforts to improve the frequency accuracy of conventional temperature-compensated crystal oscillators (TCXOs) over a wide temperature range have proved unsuccessful.

The impetus for the development of the MCXO was the need for a low-power, high-accuracy timekeeping and frequency control in application such as tactical spread spectrum systems.

This requirement is reflected in the initial specifications for the MCXO: Frequency stability of less than 5×10^{-8} over the temperature range of -55 to +85°C; hysteresis of 1×10^{-8} over that temperature range; aging of 1×10^{-10} per day and 3×10^{-8} per year; and power consumption of less than 50 mW.

The development of the MCXO is continuing, but has already succeeded in meeting or exceeding most specifications. Five units have already been tested by the U.S. Army.

OPERATION OF THE MCXO

The MCXO uses two modes of an SC-cut crystal, which are simultaneously energized. This technique is fully explained in references 1 and 2. The MCXO uses the relationship between one of the "C" mode frequencies (f_{1c} or f_{3c}) and the beat frequency (f_B), as shown in Figure 1, to obtain a digital correction.

A simplified block diagram of the MCXO is shown in Figure 2. The two outputs of the dual-mode oscillator are the crystal frequency (fundamental f_{1c} or third overtone f_{3c}) and f_B, a beat frequency derived by mixing $3f_{1c}$ and f_{3c}. The beat frequency is used as a thermometer to indicate the actual temperature of the resonator One of the crystal frequencies will be used as the basis for the output pulse train and will be corrected before outputting from the MCXO.

The f_B signal is counted, with f_{1c} or f_{3c} as the interval timing reference. The count is applied to the microprocessor, which determines, based on this count and on the known frequency/temperature characteristics of the crystal, the number of pulses that must be deleted in each unit of time. The crystal oscillator frequency (f_{1c} or f_{3c}) is selected so that, at all temperatures, it is always greater than the required output frequency. This ensures that pulses can always be deleted from the pulse train to provide the required number of pulses in each interval. Typical values are: f_{1c} = 3.38+ MHz, f_{3c} = 10 MHz, f_B = 150 kHz, and f_o = 3.38 MHz. If the calculated correction includes a fraction of a pulse, the fractional value is stored in memory, and an additional pulse will be deleted when the memory, incremented in subsequent cycles, has reached or exceeded a full pulse.

Figure 3 is a more detailed Digital Control Block Diagram. The gate period and reading of the f_{3C} counter data are controlled by a microcomputer. The microcomputer additionally extends the gate time (multiple gate times) generating a period of approximately 1 sec. Upon completion of the period, the frequency count is input to the microcomputer. The microcomputer solves a polynomial equation and, during the next period, generates the correction required to the output frequency.

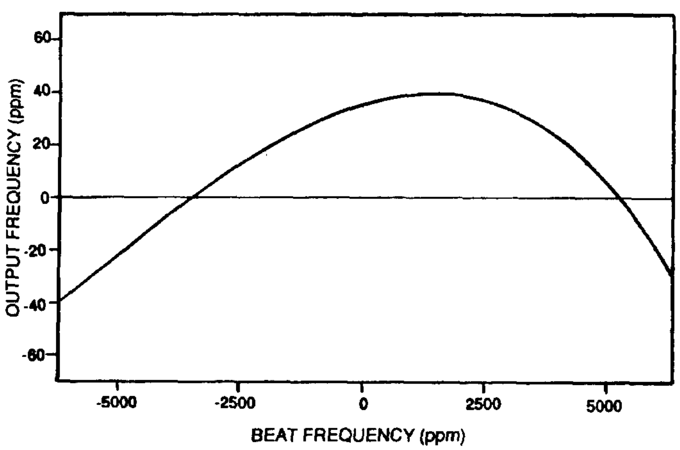

Figure 1.' Oscillator Output Frequency vs. Beat Frequency

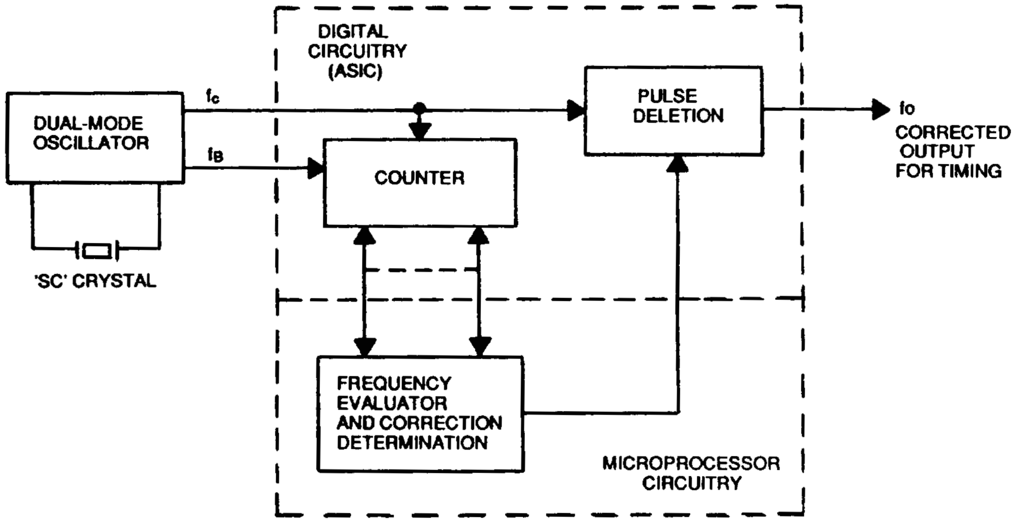

Figure 2. MCXO Block Diagram

SYSTEM EQUATIONS

The system equations for the resolution and accuracy under static and dynamic conditions are show below for an f_{3c} output frequency:

I. Beat Frequency:

$F_B = 3xF_{1C} - F_{3C}$

Where F_B = Beat Frequency

F_{1C} = Fundamental Frequency, C Mode

F_{3C} = 3rd Overtone Frequency, C Mode

II. Count Resolution Required:

F_{3C} Temp Coef = $100x10^{-6}$ from -55°C to +85°C

For Stability of $1x10^{-8}$

Enhancement Required = $\frac{100x10^{-6}}{1x10^{-8}}$ = 10,000

F_B Temp Coef = 10,000 x 10^{-6} from -55°C to +85°C

Using F_B Temp Coef

Measurement Resolution Required
= $\frac{10,000x10^{-6}}{10,000}$ = $1x10^{-6}$
(Required Enhancement)

Count F_{3C} (10+ MHz) for 1 sec period

System Measurement Resolution = $1x10^{-7}$

Yields Accuracy of $0.1x10^{-8}$

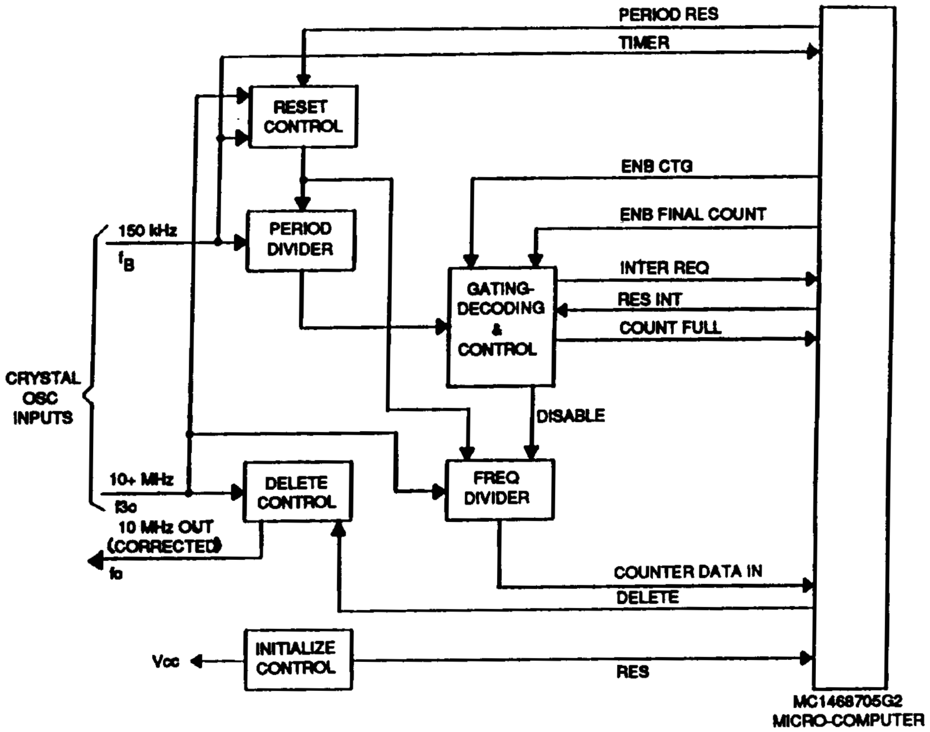

Figure 3. Digital Control Block Diagram

III. Maximum Temperature Slope Requirement:

F_{3C} Slope Max = $2\times10^{-6}/°C$

F_{3C} Slope Avg = $\frac{(100)\times(10^{-6})}{140} = 0.71\times10^{-6}/°C$

or

$\frac{F_{3C}\ Max}{F_{3C}\ Avg} = \frac{2\times10^{-6}/°C}{.7\times10^{-6}/°C} = 2.8$

F_{3C} Max = 2.8 F_{3C} Avg

..For F_{3C} Max Slope, Resolution Required

Yields Accuracy of 0.28×10^{-8}

IV. Maximum Temperature Slew:

Max Rate = 2°C/Min = 3.33×10^{-2}°C/Sec

Max Slope = $2\times10^{-6}/°C$

Max Slew = $(3.3\times10^{-2}°C/Sec) \times (2\times10^{-6}/°C)$
= 6.6×10^{-8}/Sec

Max Change = $(6.6\times10^{-8}/Sec) \times (10^7$ counts)
= .66 Counts/Sec

SYSTEM BUILDING BLOCKS

1. SC-cut quartz crystal.

An SC-cut lateral-field quartz crystal is used in this application. The advantage of using the lateral field is that the unwanted "B" modes, which are 8% higher in frequency than the "C" modes, are suppressed. This allows the use of wide-band, low Q electronic circuits with less pulling effect upon the final output frequency. The quartz crystals used for the five units tested by the U.S. Army were in C holders. Future units are planned using ceramic flatpacks, which will have the advantage of providing even better aging than has been achieved to date.

2. Dual-mode hybrid oscillator.

A custom hybrid has been manufactured in a 1 x 1 inch assembly. Internal to this hybrid are the dual-mode oscillator, a multiplier that multiplies the fundamental by 3, a mixer that provides an output at the beat frequency, and amplifiers for the beat frequency output and either the fundamental or third overtone.

3. Microcomputer.

A CMOS microcomputer is used to perform the computations to determine the pulse deletions required. The frequency vs. beat frequency curve is stored as a 5th order curve-matching algorithm in the microcomputer.

4. Gate array.

A custom gate array with approximately 2550 gates was developed to perform all of the additional digital functions not performed in the microcomputer. This gate array performs the high frequency counting and pulse deletion and provides the interface to the computer.

PERFORMANCE

The power consumption of the MCXO has been reduced since the early periods of development until it is now well below the objective of 50 mW. The power consumed in each of the major assemblies for an f_{1c} output is:

Dual-mode oscillator	8 mW
Microcomputer	18 mW
Gate array	15 mW
Total	41 mW

The frequency versus temperature, hysteresis, and aging characteristics of the MCXO were determined as part of the U.S. Army's testing of the five delivered units. Their data are presented in another paper (ref. 3). Their evaluation has verified the feasibility of achieving frequency vs. temperature stability of ± 5 x 10^{-8}, aging of 1 x 10^{-10}/day, and hysteresis of no more than 3 x 10^{-8}.

PHYSICAL DESIGN

The existing MCXO units have been supplied in a 3.3 x 2.1 x 1.75 inch package (5.2 cubic inches). This package is seen in Figures 4 and 5. A newer package is being developed to reduce the dimensions to 1.45 x 1.3 x 1.2 inches (2.2 cubic inches).

ADDITIONAL FEATURES

A calibration input from a more accurate frequency standard can be applied to the MCXO to automatically recalibrate the unit and provide improved accuracy. The

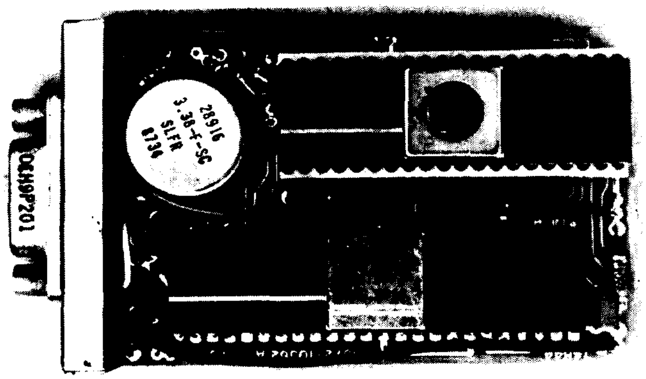

Figure 4. Top View, Cover Removed

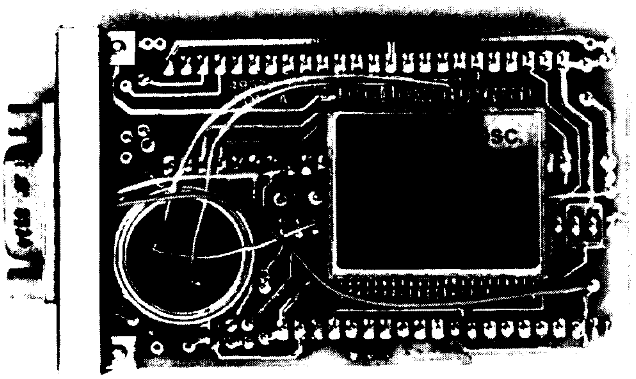

Figure 5. Bottom View, Cover Removed

calibration input is counted and compared with the output pulse count to generate an additional correction that gives the MCXO the accuracy of the frequency input.

The basic MCXO already described provides a precise pulse train output that is ideally suited for timing reference applications. As seen in the block diagram in Figure 6, a sine wave output at almost any frequency can be provided.

A spectrally pure sine wave output is generated by locking a VCXO to the MCXO. A submultiple of the VCXO is compared to a submultiple of the MCXO to develop an error frequency. This error is converted to a voltage that controls the VCXO.

A time of day (TOD) display can be incorporated in the MCXO. The output pulse train is divided down to 1 pps and this is further divided in the TOD circuit to provide 1 ppm and 1 pphr, or digital counts of seconds, minutes, and hours as required for the display.

SUMMARY

The new approach to temperature compensation in the MCXO compares the different temperature responses of the fundamental and third overtone to provide a sensitive indication of the correction needed in the output frequency. This approach eliminates the need for a temperature-controlling oven, which is needed in other approaches to maintain this accuracy. In many applications, an oven could not be used because it would increase power consumption as well as size.

This approach, which does not correct the frequency at the oscillator, also eliminates the need for external temperature-compensating components whose temperature characteristics would be used to correct those of the crystal over a limited temperature range. This MCXO approach, unlike temperature compensated crystal oscillators, does not result in frequency pulling of the oscillator. Instead, in the MCXO, the dual-mode oscillator signals are free to vary with temperature. However, the temperature characteristics of the crystal in use have been determined and stored in the microcomputer. Frequency compensation is achieved under microcomputer control by deleting pulses from an output pulse train derived from the fundamental or third overtone signal.

ACKNOWLEDGMENT

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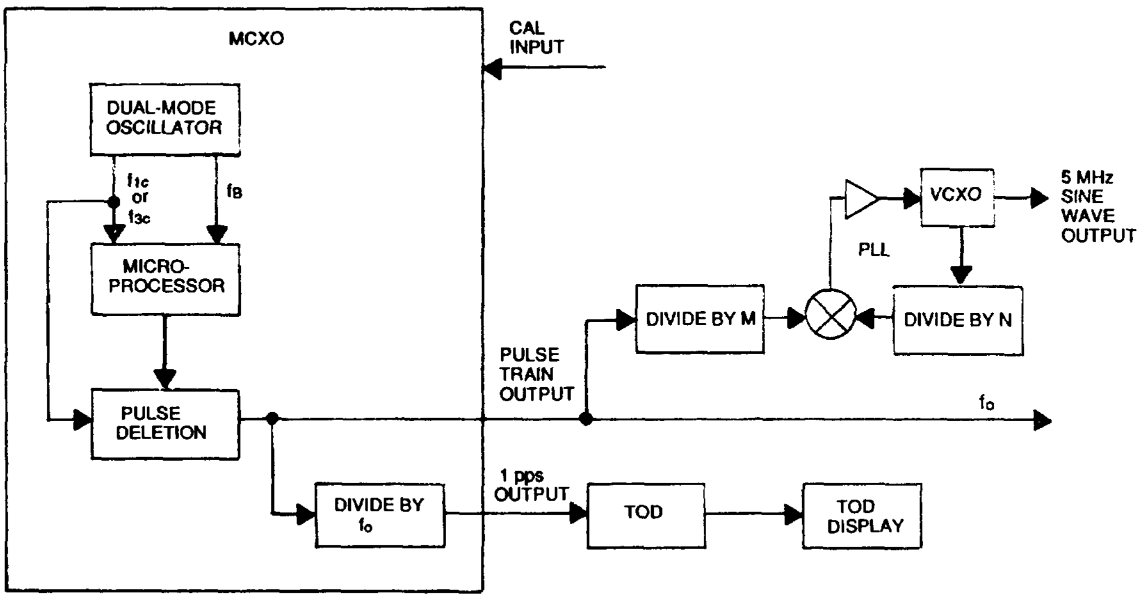

Figure 6. MCXO with Additional Features