A Temperature-Compensated DDS VFO

Use software compensation to stabilize WB2V's popular DDS VFO within 0.5 ppm from 0 to 65° C.

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Introduction

One of the challenges in the design of oscillators is to reduce temperature-induced output frequency changes. Frequency drift *versus* temperature can be a particularly onerous problem in VFO designs. Various frequency synthesis techniques can provide a low-drift alternative to the traditional analog VFO by using a more stable crystal oscillator as a reference frequency. However, crystal oscillators are not immune to drift. For example, over a temperature range of 0 to 70°C, oscillators using an AT-cut crystal may vary 20-40 parts per million (ppm) in frequency. On the HF bands, this drift can cause errors of hundreds of hertz in the output frequencies.

Many techniques to control oscillator drift have been developed. These techniques include ovens, double ovens, specially cut crystals and a great variety of temperature-compensation techniques. Temperature-compensation techniques can be difficult for amateur experimenters. A tedious process of adjusting component values may be required, and the results can be disappointing.

Lately I've been experimenting with a temperature-compensation technique that employs direct digital synthesis (DDS). In this technique, compensation is accomplished in software rather than hardware. With this compensation technique, I was able to demonstrate a DDS VFO that had 0.5 ppm drift over a temperature range of 0 to 65°C. Fig 1 shows the measured VFO drift with and without compensation.

A Little History

My experiments employed a temperature-compensation system that was invented[1] in 1973. Fig 2 is a block diagram of that system. The system works by adjusting the control inputs of a "presettable" frequency divider. The adjustment is made a function of temperature so that it cancels the drift in the reference oscillator, producing a divider output that is temperature compensated.

It's probably safe to say that in the early '70s, this system required many

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[1]Notes appear on page 45.

parts. However, with present-day microcontrollers and single-chip direct-digital synthesizers, the system can be implemented using two off-the-shelf chips, along with a few other components. A microcontroller can be programmed to calculate a frequency control word "W" for a DDS chip, where "W" is a function of both temperature and another external input.

A DDS chip is a convenient way to implement the presettable frequency divider portion of the system. An interesting example of using direct digital synthesis for temperature compensation was published[2] in 1989. It combined DDS with a novel temperature-sensing scheme,[3] where the crystal itself was used to sense temperature. This oscillator was reported[4] to have a stability of 0.03 ppm from –55 to 85°C.

The particular implementation for my experiments is shown in Fig 3. This system is very similar to a DDS VFO I've described previously.[5] On the hardware side, the difference is the addition of a resistor/thermistor voltage divider and the substitution of a microcontroller that contains an analog-to-digital converter (ADC). On the software side, the code[6] is changed so that it adjusts the data sent to the DDS chip according to the temperature indicated by the thermistor.

Test Setup

In order to collect frequency-versus-temperature data, I built a small, insulated test chamber. Thermoelectric modules[7] (also known as Peltier-effect modules) were used to pump heat in or out of the chamber. By controlling the current through the thermoelectric modules, the chamber temperature could be varied. My construction techniques limited the temperature range to 0 to 65°C.

The resolution was limited to one-degree steps by the control circuit—not state-of-the-art performance, but it saved many trips to the kitchen, and freed up the refrigerator and oven for normal use.

A crystal oscillator along with a thermistor, buffer amplifier and voltage regulator were placed in the thermal test chamber. The oscillator was a common-base Colpitts using a fifth-overtone AT-cut crystal. A bead thermistor was held in place on the crystal using heat-shrink tubing. The buffer amplifier was a pair of 74AC04 inverters wired in parallel. Two 78L05s were used for voltage regulation, one for the oscillator and one for the buffer amp. The buffer amplifier output was ac coupled to a short run of coax. At the DDS-chip clock pin, the coax was terminated with 100 Ω to ground and 100 Ω to V_{DD}.

The DDS chip and microcontroller were kept outside the thermal chamber to reduce the heat load. A DDS VFO—minus the microcontroller—

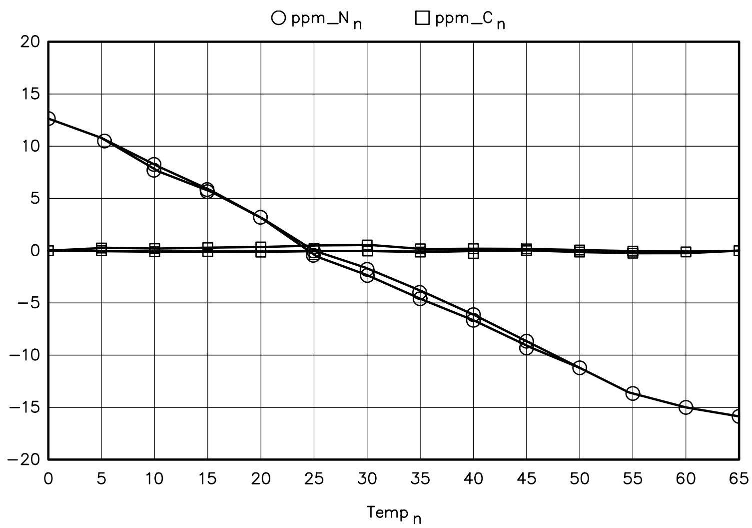

Fig 1—DDS VFO output drift with/without compensation.

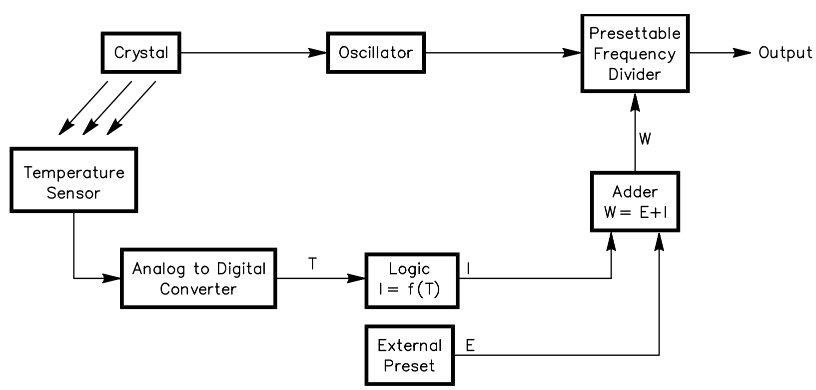

Fig 2—An externally compensated oscillator, circa 1973.

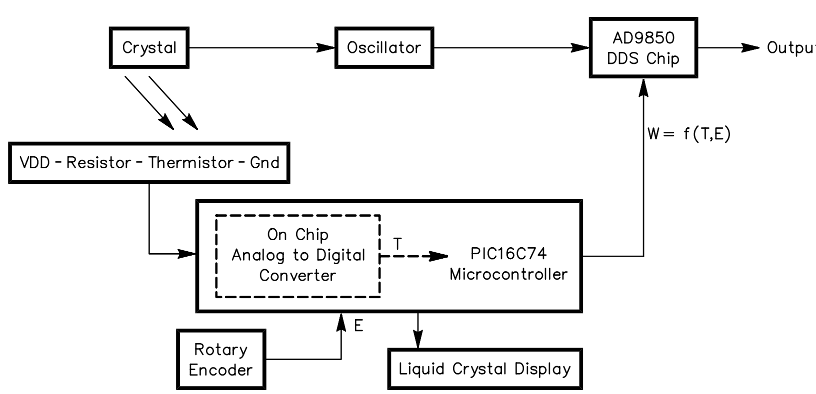

Fig 3—A temperature-compensated DDS VFO.

was mounted on a piece of perforated board along with a PIC16C74 microcontroller, LCD and shaft encoder. These were wire-wrapped together, with the PIC16C74 wired to replace the original PIC16C54 on the DDS VFO. A switch was connected to one of the microcontroller inputs so that compensation could be turned on or off. The complete setup is shown in Fig 4.

Factors Affecting Temperature Compensation

Hysteresis

Hysteresis is a significant problem for any temperature-compensation scheme. Here, hysteresis means that the oscillator frequency at a particular temperature depends on what the previous temperature was. A measurement of this effect can be seen in Fig 5. Data for the plot was taken in 5° steps around the cycle 25°, 65°, 0°, 20°C. After each step, 30 minutes were allowed for everything to reach a stable temperature.

Much of the literature on this subject agrees on one thing: The exact causes of hysteresis are not well understood. Consequently, it is not possible to control hysteresis very well. There are some oft-cited observations[8] about hysteresis:

- The crystal itself exhibits hysteresis.
- Other oscillator components can make the problem worse, often dominating.
- The effect is larger over wider temperature swings.
- The hysteresis of different crystals may have different "signs." That is, the frequency for increasing temperature may be higher or lower than the frequency for decreasing temperatures.
- The magnitude of the hysteresis may vary significantly from unit to unit.

Unit-to-Unit Variations

The frequency-versus-temperature characteristic of crystals may vary greatly from unit to unit. This means that in order to achieve good results, each oscillator must be individually characterized. The compensation data for one oscillator will not work well for another. For example, Fig 6 compares two copies of the oscillator circuit I used.

Numerical Issues

Temperature-compensation techniques rely on a known relationship between an oscillator's frequency and temperature. This relationship is measured, then stored in the microcontroller's memory. The frequency-versus-temperature data can be stored as a table. Then interpolation can be used to calculate points between table entries. Another storage method is to fit the measured data to a polynomial and store only the polynomial coefficients. There are inevitable differences, or *residuals*, between the measured data and the stored representation. These residuals can be reduced by using higher-order polynomials or improved interpolation techniques.[9, 10]

Since my experiments were carried out over a limited temperature range, the problem of residuals was greatly reduced. Crystals with an AT cut have an S-shaped frequency-versus-temperature characteristic. Likewise, a plot of the voltage versus temperature of a resistor-thermistor voltage divider displays a complex curve. Over a limited temperature range, however, the relationship of thermistor voltage to frequency is nearly a straight line. This can be seen in Fig 6.

The resolution of the ADC is in play. The slope of the frequency drift versus thermistor voltage for oscillator B was about 12 ppm/V. Using an 8-bit ADC over a 5-V input range provides a resolution of about 20 mV. This translates into a frequency resolution of about 0.23 ppm. For oscillator A, the limit was about 0.33 ppm.

On the other hand, the resolution of the AD9850 DDS chip was not a significant factor, except at low output frequencies. With a 32-bit accumulator, and the reference oscillator at 120 MHz, the DDS frequency resolution is about 0.028 Hz. This is 0.1 ppm if the VFO output frequency is 280 kHz, but at 5 MHz, the DDS resolution is 0.0056 ppm.

Thermal Time Constants

Thermal time constants can cause more problems. Some time is required for the resonating portion of the crystal to reach the same temperature as a thermistor on the outside of the crys-

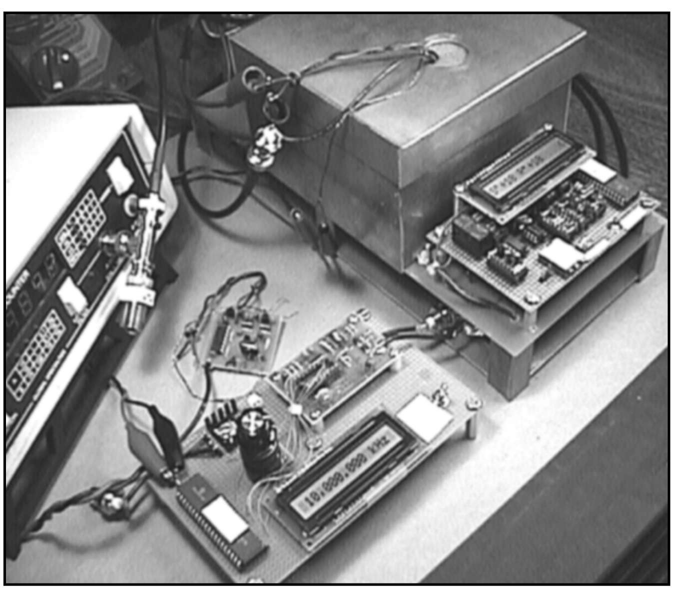

Fig 4—A Photograph of the test setup, showing: thermal chamber, DDS VFO assembly, oscillator assembly and a frequency counter.

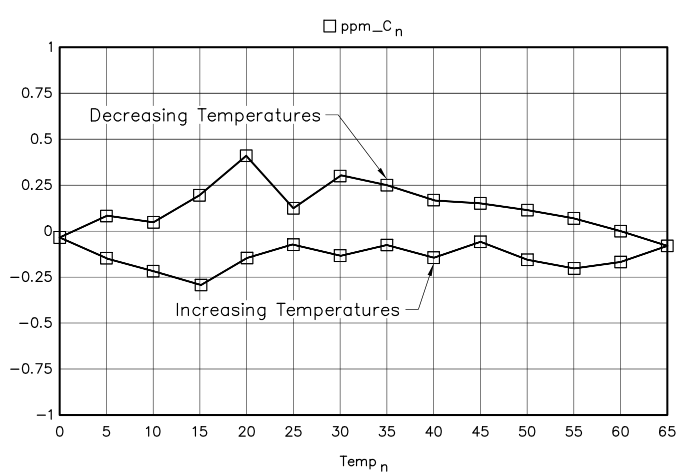

Fig 5—Measured DDS VFO hysteresis.

tal holder. Power-on warm up is one situation where thermal time constants can be noticed; another is during a rapid temperature change.

My frequency counter was too slow to directly measure the effects of thermal time constants, but I was able to observe the warm-up drift by listening to the VFO output on a receiver. The signal could be heard to shift back and forth a few hertz as the temperature changed, but it was difficult to distinguish between the effects of thermal time constants and the limited resolution of the ADC.

Conclusion

These experiments verified the effectiveness of adding temperature compensation to a DDS VFO. A significant reduction in frequency drift was obtained with very little additional hardware. However, time and effort were required to measure the frequency-versus-temperature characteristic of the reference oscillator.

Software-compensation techniques provide a great deal of flexibility. They're able to compensate for complex relationships between temperature and frequency. For the limited temperature swing of 0 to 65°C, the oscillator was characterized quite closely by linear interpolation. For wider temperature swings, a more sophisticated interpolation or curve-fitting technique should be used.

Good results were obtained using an 8-bit ADC. A 10-bit converter may give better results, but at some point, hysteresis and thermal time constants will limit the stability that can be achieved.

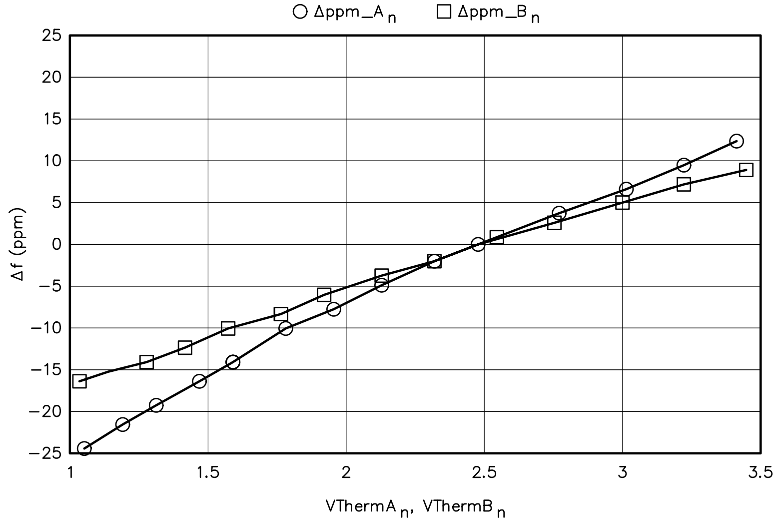

Fig 6—Drift versus thermistor voltage for oscillators A and B.

Notes

[1]US Patent 3,719,838: "Temperature Compensating Digital System for Electromechanical Resonators," Ralph Peduto and Jan Willem L. Prak, issued March 6, 1973, see claims 12-14.

[2]A. Benjaminson and S. Stallings, "A Microcomputer-Compensated Crystal Oscillator Using a Dual-Mode Resonator," *Proceedings of the 43rd Frequency Control Symposium*, 1989.

[3]S. Schodowski, "Resonator Self-Temperature Sensing Using a Dual-Harmonic-Mode Crystal Oscillator," *Proceedings of the 43rd Frequency Control Symposium*, 1989.

[4]A. Benjaminson and B. Rose, "Performance Tests on a MCXO Combining ASIC and Hybrid Construction," *Proceedings of the 45th Annual Symposium on Frequency Control*, 1991.

[5]C. Preuss, WB2V, "Building a Direct Digital Synthesis VFO," *QEX*, Jul 1997, pp 3-7.

[6]You can download the experimental code with the new function from the ARRL Web **http://www.arrl.org/files/**. Look for DDS_VFO.ZIP.

[7]URL **http://www.itiferrotec.com** has a lot of technical information about thermoelectric modules.

[8]R. Filler, "Thermal Hysteresis in Quartz-Crystal Resonators and Oscillators," *Proceedings of the 44th Frequency Control Symposium*, 1990.

[9]M. Frerking, "Crystal Oscillator Design and Temperature Compensation", Van Nostrand Reinhold Company, 1978, Chapter 10.

[10]R. Filler, "Frequency-Temperature Considerations for Digital Temperature Compensation," *Proceedings of the 44th Frequency Control Symposium*, 1990. □□