APPLICATION NOTE

Fine Frequency Control Using the SKY72300, SKY72301, and SKY72302 Dual Synthesizers/PLLs

Many techniques currently exist for synthesizer frequency output control. These techniques, from simple to complex, manipulate the crystal oscillator to maintain a specific output frequency. All of these techniques have associated cost and parts count considerations.

This Application Note describes the fine frequency control of Skyworks SKY72300, SKY72301, and SKY72302 fractional-N synthesizers using a Voltage Controlled Oscillator (VCO). This method is a simple and low-cost alternative to pulling the crystal reference frequency to manipulate the final output frequency. The technique has the following applications:

- Radio calibration
- Automatic Frequency Control (AFC)
- Reference crystal accuracy
- Reference crystal temperature compensation
- Reference crystal aging compensation
- Doppler correction

Step Size

The SKY72300, SKY72301, and SKY72302 group of synthesizers has 18-bit fractionality on the main synthesizer, which provides 262144 steps with respect to the internal reference frequency. This is also the step size available at the VCO output frequency.

The formula used to calculate the step size is:

$$\text{Step size (Hz)} = \frac{\left(F_{xtal}/R\right)}{2^{18}}$$

where: F_{xtal} = the crystal frequency reference.

R = an integer value ranging from 1 to 32 used to divide the crystal reference frequency to arrive at the internal reference frequency, F_{ref} (also referred to as the comparison frequency).

Example 1:

Using a 20 MHz crystal and a reference division of R = 1:

$$\text{Step size} = \frac{(20\,\text{MHz}/1)}{262144} = 76.29\ \text{Hz}$$

This represents the minimum step size achievable with a 20 MHz crystal oscillator and R = 1. If this synthesizer operated with a 1.8 GHz VCO, it would be tunable in 76 Hz step sizes at 1.8 GHz.

Example 2:

Using a 20 MHz crystal and a reference division of R = 32:

$$\text{Step size} = \frac{(20\,\text{MHz}/32)}{262144} = 2.38\ \text{Hz}$$

This represents the minimum step size achievable with a 20 MHz crystal oscillator and R = 32.

Frequency Resolution

Fine resolution is achieved by having a very fine step size of 2 Hz (R = 32) to 76 Hz (R = 1) as indicated above. This step size is independent of the output frequency and applies to the SKY72300 and SKY72301. The SKY72302 has a step size four times greater on the main synthesizer due to a fixed divide-by-4 to the divider input.

Frequency resolution can also be measured in parts per million (ppm) relative to the output frequency. The formula used to calculate the resolution in ppm is:

$$\text{Resolution (ppm)} = \frac{\left(\frac{(F_{xtal}/R)}{2^{18}}\right)}{F_{out}} \times 10^6$$

Example 3:

Calculate the frequency resolution of a 1.9 GHz Phase Locked Loop (PLL) output by using a 20 MHz crystal where R = 1.

$$\text{Resolution (ppm)} = \frac{\left(\frac{(20\ \text{MHz}/1)}{2^{18}}\right)}{1.9\ \text{GHz}} \times 10^6 = 0.04\ \text{ppm}$$

Radio Calibration

The ability to calibrate a radio or a PLL output using a high resolution fractional-N synthesizer is much simpler than using AFC, or characterizing crystal oscillators for temperature drift or aging. This type of calibration offers many advantages.

During production, radios must be tuned to perform at specific frequencies within a predetermined tolerance. Tuning radios can be time consuming and expensive. Radios frequently have a tunable component that is adjusted by a technician to calibrate the radio frequency output. A major reason for this requirement is due to the absolute frequency inaccuracy of the crystal.

Crystal oscillators typically contain small frequency errors. A 10 MHz crystal oscillator, for example, might actually be

10.000005 MHz. If the value of N is 250, the output frequency would be 2.5 GHz. This translates to a PLL output inaccuracy of 1250 Hz. This error must be corrected before shipping the radio product.

Further, once the product has been shipped the crystal frequency can change due to temperature drift and aging. In other words, the frequency output value constantly changes. The amount is dependent upon the type of oscillator being used. Temperature drift and aging of the crystal oscillator are relevant in the field, whereas the initial crystal inaccuracy is an issue in manufacturing.

A common method used to correct these problems involves the use of a Voltage-Controlled Crystal Oscillator (VCXO). In this method, the system determines if the crystal frequency is either high or low and must be adjusted. A correction is introduced and the crystal returns the output frequency back to its original desired value. This method involves hardware components and software algorithms (another method is proposed in the AFC section of this document in which the output frequency of the VCO is corrected).

A simpler method used to correct either the crystal frequency inaccuracy or the VCO output is to allow the crystal frequency to drift naturally and perform a calibration of the crystal relative to the output. To make this calibration, the output of the VCO is measured and a simple calculation made to determine the actual crystal frequency.

If a fractional-N PLL is programmed to output a given frequency of 2.45617 GHz, the synthesizer performs a calculation to determine the actual fractional-N value required to bring the output of the VCO to 2.45617 GHz. This frequency is based on the value of the crystal frequency calculated with Equation 1:

$$N = \frac{F_{out}}{\left(F_{xtal}/R\right)} \quad (1)$$

Example 4:

Calibrate a PLL that operates at 2.45617 GHz using a 20 MHz crystal and a reference division of R = 2.

Using Equation (1):

$$N = \frac{2.45617\ GHz}{\left(20\ MHz/2\right)} = 245.617$$

Therefore, the required N value for the PLL to produce the desired frequency output is 245.617.

When the synthesizer outputs the desired frequency, it would be the internal reference frequency multiplied by the value of N, or approximately 2.45617 GHz in this case. The internal reference frequency, F_{ref}, is the crystal frequency (F_{xtal}) divided by the reference divider, R.

Measure the actual output frequency of the PLL. If the output is determined to be 2.45637 GHz, the amount of error is equal to 200 kHz. This also indicates that the crystal value is in error.

If the measured output is substituted for the desired output in Equation 1, the actual crystal oscillator output frequency is calculated as follows:

$$F_{actualxtal} = \frac{F_{measuredout} \times R}{N} = \frac{2.45637 \times 2}{245.617} = 20.001628\ MHz$$

The actual crystal frequency calculated above is 1628 Hz higher than expected. The new crystal frequency value can be placed in non-volatile memory inside the radio to be used for future calculations.

The crystal frequency error of this example can also be expressed as 81.4 ppm:

$$Crystal\ \ frequency\ error\ (ppm) = \left|\frac{F_{xtal} - F_{actualxtal}}{F_{xtal}}\right| \times 10^{6}$$

$$= \left|\frac{20\ MHz - 20.001628\ MHz}{20\ MHz}\right| \times 10^{6} = 81.4\ \ ppm$$

If the new crystal frequency of 20.001628 MHz is used in Equation (1), a new value for N can be determined:

$$N = \frac{2.45617\ GHz}{\left(20.001628\ MHz/2\right)} = 245.596$$

In summary, the actual crystal frequency was determined to be 20.001628 MHz, which is a correction of 81.4 ppm. The new N value required to achieve the originally desired 2.45617 GHz output is now 245.596.

Since the crystal frequency is actually 20.001628 MHz, this number can be used in all of the frequency calculations until the calibration needs to be performed again. In production, this means automating the procedure without the need for tuning elements since all corrections are performed in software.

This has one key benefit. Radio manufacturers no longer depend on crystal vendors to manufacture crystals to very tight frequency tolerances since they can simply correct for these by using a high resolution synthesizer. In fact, similar frequencies can easily be substituted with only small changes in performance due to higher N values. Using this method, a 19 or 21 MHz crystal could easily be used.

This type of calibration is not limited to final production testing. If the radio system used in the field can determine the frequency output, this method could be used in the radio for self-calibration in the field and for updating the crystal frequency value in non-volatile memory.

Since the crystal frequency can be allowed to drift, it's only necessary to know the actual crystal frequency at any given moment. The factory calibration would have previously corrected for the initial inaccuracy of the crystal oscillator. Therefore, this is the starting point for any future drift of the crystal frequency.

If this calibration method is continually used in the field, the effects of aging and temperature drift can be easily corrected in a TCXO. If calibration is performed often enough, and depending on system requirements, perhaps even a free running crystal could be used. With such an application, the system would be able to compensate for any temperature drift without requiring any knowledge of the system temperature.

There are several advantages offered by this method:

- Any similar crystal frequency could be substituted (e.g., 24.1 or 23.9 MHz)
- The absolute accuracy of the crystal frequency is no longer important since this can be corrected in production testing
- Crystal aging now can be field corrected
- Temperature correction of the crystal can be performed in real time without requiring prior knowledge of the temperature characteristics of the crystal or the actual operating temperature of the radio

Automatic Frequency Control (AFC)

AFC is a method of adjusting the output frequency of a PLL up or down based on the system's ability to measure the actual operating frequency or the ability to track a drifting carrier frequency in a remote transmitter. In either case, the correction can be performed directly by the synthesizer. Typically, the use of a VCXO achieves AFC.

AFC can alleviate the need to perform any correction due to crystal inaccuracy, temperature drift, or aging of either a local receiver or a remote transmitter.

A VCXO can be a crystal oscillator, a Temperature-Compensated Crystal Oscillator (TCXO), or an Oven Controlled Crystal Oscillator (OCXO) with a varactor diode controlled by an external voltage. The varactor diode responds to a voltage that corrects the crystal oscillator frequency for crystal accuracy offset, temperature drift, or aging effects.

VCXOs are typically used in systems with 200 kHz channel spacing or less. A VCXO has a frequency versus tuning voltage slope and also a linearity associated with this slope. The linearity is specified as the minimum and maximum slopes of frequency versus voltage.

If a VCXO is operated with large frequency variations, it can cause stressing which results in degraded phase noise, aging, and temperature stability. This can partially negate the very reasons for having selected a VCXO in the first place.

If a system has the capability to correct the crystal, then it is reasonable to assume that this correction could also be applied to the synthesizer output as well. This has several advantages:

- Cost savings. The expensive VCXO can be replaced by a less expensive crystal oscillator.
- Reduced power. With either the SKY72300, SKY72301, or SKY72302 on-chip crystal oscillator, much less power is used than with an external oscillator.
- Improved close-in phase noise. The phase noise of a crystal oscillator is lower than a typical VCXO. The actual corrections are smaller because the crystal is not constantly being corrected (stressed). This can cause further variations in aging, temperature sensitivity, and phase noise.
- No additional frequency versus tuning voltage slope or associated linearity. Large variations relative to a VCXO are well within the normal operation of the SKY72300, SKY72301, or SKY72302 fractional-N synthesizers.

Crystal Characteristics

Crystals made from quartz are available in frequencies typically ranging from 10 to 150 MHz. There are various ways to cut quartz crystals that affect the performance. The "AT" cut has become the most popular because it operates at relatively high frequencies and gives excellent frequency versus temperature stability.

The typical frequency range of a crystal is about 30 MHz. Above 30 MHz, the cut of material becomes too thin for practical production. For frequencies above this point, odd integer multiples such as the 3rd, 5th, 7th, or 9th overtone of the fundamental frequency are used.

Reference Crystal Accuracy

The accuracy of crystal oscillators also varies. Expensive, accurate crystals use a deposition technique to grow the material until crystals reach the desired frequency. These expensive crystals have the same phase noise and temperature characteristics as the inexpensive crystals but have a lower initial frequency offset error.

This offset error is usually expressed as a tolerance in ppm at room temperature. The actual output frequency can be anywhere within the specified range.

Example 5:

Tolerance = ±10 ppm @ 25 °C.

If a low-cost crystal with a possible large frequency offset is used, it is possible to correct for inaccuracies in final testing. By performing a measurement of the frequency output of the PLL synthesizer, and comparing this with the desired output, the error can be calibrated out of the system by storing a correction factor in non-volatile memory.

The amount of frequency offset seen in a typical system does not exceed the synthesizer's ability to perform the correction. The correction factor itself can be placed in non-volatile memory. This method allows a cost sensitive product, such as a multi-mode handset, to have an inexpensive crystal.

Reference Crystal Temperature Compensation

The output frequency of a crystal oscillator drifts with the external temperature. This drift is expressed in stability ppm at room temperature. A frequency versus temperature curve is illustrated in Figure 1. Typical temperature drift of a crystal can be up to ±30 ppm over the operating temperature range.

Example 6:

Stability = ±30 ppm (–10 °C to +60 °C).

TCXOs have an added thermistor/resistor circuit that drives a varactor diode connected in series with the crystal. This circuit cancels the crystal temperature characteristics. The circuit improves the temperature stability of the crystal. However, it never entirely eliminates the temperature drift.

Typical temperature drift of a TCXO can be 2 ppm over the operating temperature range.

The SKY72300, SKY72301, and SKY72302 fractional-N synthesizers have an internal crystal oscillator. If a TCXO can be replaced by the internal oscillator and a basic crystal, a cost and power savings compared with the TCXO can be achieved. Replacing the TCXO means that the crystal temperature characteristics need to be corrected.

Many radio systems now have software to measure system temperature. If the temperature is known, it is only necessary to develop the curve representative of the temperature characteristics of the crystal. Typical curves for the crystal can sometimes be obtained from the manufacturer.

With this knowledge, synthesizer frequency output can be adjusted at the VCO using software in the microprocessor or Digital Signal Processor (DSP) that controls the synthesizer.

If the radio system does not have the ability to measure temperature, then a simple circuit involving a thermistor and a low-cost Analog-to-Digital Converter (ADC) can be used. The added cost would reduce the cost saving to be had by the elimination of a TCXO. However, with the temperature measured through software control, the system designer can use that temperature in other parts of the system.

Crystals do not all have the same temperature characteristics from unit to unit. This is a function more of the tolerances of the oscillator circuitry and the compensation network than of the crystal characteristics. TCXO manufacturers typically mark the package with an “offset” frequency either in Hz or ppm. Having the crystal oscillator circuitry in a very repeatable BiCMOS process may minimize the effect.

However, since the TCXO manufacturer can manually adjust the offset, it can be performed as part of the automated test set up, where the actual output at room temperature can be measured and an offset in Hz entered into the system memory.

Another benefit of adjusting crystal compensation in software is the fact that the designer is not required to state the operating temperature range when specifying the oscillator, as would be the case with a TCXO. This is because the temperature compensation circuit in a TCXO can not completely compensate for the individual characteristics of the crystal. The manufacturer will only match the thermistor/resistor network to the crystal curve over the specified temperature range.

As illustrated in Example 3, a 1.9 GHz system using a 20 MHz crystal can be corrected by 0.04 ppm or by 76 Hz. This can eliminate the requirement for an expensive TCXO, which reduces the system cost.

Crystal Aging Compensation

Crystal output frequencies drift with time. Aging is caused by thermal effects such as temperature cycling, high ambient temperature or even high drive levels, for example.

The average drift of a crystal can be 2 to 3 ppm per year. This means that the VCO output frequency may not be in the center of the channel after a number of years. This can render the PLL and the radio inoperative. The amount of drift that can be tolerated is system dependent.

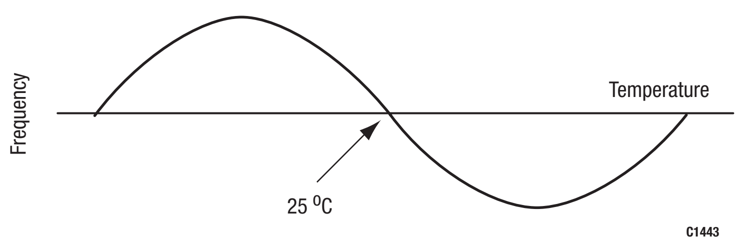

Figure 1. Crystal Frequency Versus Temperature Curve

The frequency error per year attributed to aging can be calculated by Equation 2:

$$Aging\ (ppm)/\ year = \frac{\Delta F}{F_{out}} \times 10^6 \tag{2}$$

where: ΔF= the change in the crystal frequency over a period of one year.

Example 7:

Calculate the total frequency error after 3 years for a 1.9 GHz Global System for Mobile communications (GSM) radio using a 200 MHz high-side Local Oscillator (LO) and a crystal that ages 3 ppm per year. Using Equation (2):

$$3\,ppm\ /\ year = \frac{\Delta F}{2100\ MHz} \times 10^6$$

$$\Delta F = 6.3\ kHz\ /\ year$$

Therefore, after 3 years the total drift would be 18.9 kHz. In a GSM system, the channel spacing is 200 kHz. This means that after only 3 years, the actual frequency would be approximately 20 percent away from the center of the channel due to aging, alone. If the GSM handset in this example is part of a multi-mode, multi-band handset that alternately uses (fall-back mode) the Advanced Mobile Phone System (AMPS) mode, the errors in AMPS mode could also be calculated.

Example 8:

Calculate the total frequency error after 3 years for an 894 MHz AMPS radio using a 45 MHz high-side LO and a crystal that ages 3 ppm per year. With a 45 MHz high side LO, the output frequency of the PLL synthesizer would be 939 MHz. Using Equation (2):

$$3\,ppm\ /\ year = \frac{\Delta F}{939\ MHz} \times 10^6$$

$$\Delta F = 2.8\ kHz\ /\ year$$

Therefore, after 3 years the total drift would be 8.4 kHz. In an AMPS system, the channel spacing is 30 kHz. Even though the total drift over 3 years is less than what it would be with the GSM system in Example 7 relative to the channel spacing, a frequency drift of over 50 percent has occurred in the AMPS example.

The average drift of a crystal can be provided by the manufacturer or it can be measured. Sample units can be measured over a period of time and statistical results maintained. The longer the period of time over which the tests are performed, the better the crystals can be characterized. This data can be fed into non-volatile memory aboard the system and any corrections can be performed at specific time intervals.

Doppler Correction

Many of the radio systems used today, such as cellular phones, pagers, and satellite handsets have one or both terminals mobile. This movement causes a change in frequency up or down. The frequency shift can be determined using Equation (3):

$$Doppler\ shift\ (Hz) = \frac{vf}{c} \tag{3}$$

where: v = Vehicle velocity (m/s)

f = Frequency of operation (Hz)

c = Speed of light (3×10^8 m/s)

Example 9:

Calculate the Doppler shift of a cellular phone operating at 1.9 GHz in a vehicle travelling at 100 km/h (27.7 m/s). Using Equation (3):

$$Doppler\ shift\ (Hz) = \frac{27.7\ m/s \times 1.9\ GHz}{3 \times 10^8\ m/s^{-1}}$$

$$Doppler\ shift = 176\ Hz$$

The 176 Hz shift can be corrected to a resolution of 76 Hz.

In the case of a satellite handset communicating with a Low Earth Orbit (LEO) satellite, the Doppler shift can be 25 kHz. Therefore, there is a significant requirement for correcting satellite handsets.

In the case of the cellular example, when the automobile is travelling away from the base station, the Doppler shift is subtracted. When the automobile is travelling toward the base station, it is added.

One problem associated with Doppler correction is that the figure is not a constant. The automobile often does not travel directly towards or away from the base station, but rather travels at varying angles or is at rest. This means that the Doppler shift can be anywhere from zero to the maximum value, as calculated above.

The amount of inaccuracy that can be tolerated is dependent upon the system requirements. However, the shift in ppm can be calculated using Equation 4:

$$Doppler\ shift\ (ppm) = \frac{Doppler\ shift\ (Hz)}{F_{out}} \times 10^6 \tag{4}$$

Example 10:

Calculate the Doppler shift in ppm with an operating frequency of 1.9 GHz and a Doppler shift of 176 Hz. Using Equation (4):

$$Doppler\ shift\ (ppm) = \frac{176\ (Hz)}{1900\ MHz} \times 10^6$$

$$Doppler\ shift = 0.09\ ppm$$

The non-correlated effects of Doppler shift, temperature drift, crystal accuracy, and aging can be calculated with Equation 5:

$$Error\ (ppm) = \sqrt{Doppler^2 + TempDrift^2 + Accuracy^2 + Aging^2} \quad (5)$$

Example 11:

Calculate the total non-correlated frequency error by using the individual error values from Examples 5, 6, 7, and 10. Using Equation (5):

$$Error\ (ppm) = \sqrt{0.09^2 + 30^2 + 10^2 + 3^2}$$

$$Error = 32\ ppm$$

The result is a non-correlated total frequency error of 32 ppm.

Crystal Temperature Characterization

A TCXO is realized in software by characterizing crystals according to temperature. These crystals are temperature-characterized by placing them in an oven and measuring the frequency output versus temperature curve over the desired temperature range. The number of temperature points is dependent on the final system accuracy requirement. Typically a calibration point every one to ten degrees could be used. These values can then be used to correct the output frequency of the PLL.

As illustrated in Figure 1, the crystal frequency versus temperature curve typically crosses the zero axis at about 25 °C. Variations in the load capacitors of the crystal oscillator circuit and the manufacturing tolerances affecting the thickness of the crystal can introduce an initial frequency offset in the frequency versus temperature curve.

To reduce the effect of these variations, an output frequency can be generated by the PLL synthesizer in final testing performed at 25 °C. The frequency can be measured and compared to the desired frequency. This error would be translated into an offset for the PLL. The value would be placed in non-volatile memory and used to permanently offset the synthesizer output.

Alternatively, the correction could be performed as described in the Radio Calibration section of this document, where the error is used to recalculate the crystal reference frequency.