Basic Crystal Oscillator Design Considerations

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INTRODUCTION

In the world of crystal oscillators there are a myriad of design variations, with an even wider spectrum of applications. Experience teaches circuit designers that always considering every factor influencing design complexity and reliability, whether designing an oscillator for a one-shot application or a production run of thousands, is wise.

In deciding which type of oscillator is appropriate, four primary factors must be considered: the type of application (fixed or modulated); the frequency of operation; the load that the oscillator will output into; and the parts available.

The basic requirements for any functional oscillator circuit are: 1) a phase shift through the oscillator loop (consisting of an amplifier, reactive components, and the crystal) of either 0° or 360°; 2) an open loop gain of greater than 1.0 at the operating frequency; and 3) a "negative resistance" generated by the circuit greater or equal in magnitude to the equivalent series resistance of the crystal.

Below are the basic design criteria for the most popular types: both IC and transistor based Pierce, Colpitts, and Common Base crystal oscillator circuits.

PIERCE OSCILLATORS

In many instances Pierce-type IC oscillators may be appropriate. Stand-alone or incorporated into a complex device, this configuration uses a simple inverter to provide 180° of phase shift, with the additional 180° supplied by two "pi" capacitors. Loop gain is optimized by specifying a lower output capacitance value than that of the input. The crystal parallel-resonates with the series combination of capacitors as the load, and overtone operation can be accomplished by incorporating a mode trap at the front end (see Fig. 1). The trap should be tuned midway between the desired overtone frequency and its predecessor. A resistor connecting the input and output of the circuit adds linearity to the gate and adjusts amplification. It can also be used for third overtone selection, negating the need for the mode trap.

The simplest single pair inverter (equiv.: Harris 74HCU04) is most desirable, as it more easily achieves linearity, reduces the possibility of latch-up, and also provides the fastest speed - limited only by the propagation delay characteristics of the fabrication technology. All standard IC inverters have a significant disadvantage: their amplifying characteristics aren't as easily fashioned, as input impedances are fixed and output impedances are at best "negotiable." Bandwidth can be adjusted to a limited extent by changing the feedback resistor (usually from 2.2K to 100K). For optimum performance and repeatability, these inverters should not be utilized beyond their 3db point.

Supply-line bypassing techniques are important when utilizing IC oscillators. Since most have a relatively narrow linear region, their amplifying characteristics can easily be affected by supply noise during system power up. Neglecting to adequately bypass voltage transients will result in: a lack of oscillator start, non-crystal controlled oscillation (self-oscillation), or crystal-controlled oscillation modulated by self-oscillation frequencies.

If the design is intended to drive circuits or devices other than members of the standard
digital logic families, or if the application requires a more sinusoidal output, the designer must consider alternative discrete-based oscillator configurations. Completely adaptable and better suited to load matching, a transistor-based oscillator is more complex to design but significantly increases flexibility.

The simplest form of a Pierce-type transistor oscillator (see Fig. 2) mirrors the IC design, with the amplifier providing 180° of phase shift, and the opposing 180° provided by the pi capacitors and the crystal. With amplifier design following conventional rules for input and output impedance, and since the transistor-based Pierce type is primarily applied in a common-emitter configuration, it is more suitable for driving medium to high impedance loads. Primarily utilized for frequencies above 10 MHz, a crystal drive is normally quite high, sizable voltage gain provides a sinusoid output of respectable amplitude. These characteristics can be advantageous for high frequency applications, with an abundance of power available for driving high impedance overtone modes. Excess drive will cause unwelcome performance in the crystal however, potentially exciting spurious & coupled mode responses.

COLPITTS OSCILLATORS

The Colpitts configuration (see Fig. 3) places the crystal from the base of the transistor to ground. As it employs an emitter-follower, the bulk of the phase shift is provided by the capacitors, with the balance provided by the feedback path through the crystal. The crystal is parallel-resonant with the series combination of the Colpitts capacitors. Loop gain is optimized with a base-emitter capacitor lower in value than the emitter-ground capacitor. In applications above 70 MHz however, it is often beneficial to reverse this ratio, as additional signal feedback to the base may be required.

The Colpitts can be utilized in either a common-emitter or common-collector configuration. This allows compatibility whether you are driving high, medium, or low impedance applications. In the common-collector configuration, the resistor between the collector and source voltage is normally eliminated for optimum power transfer to the load. The load’s equivalent impedance should also be considered when arriving at the physical value for the emitter-ground capacitor. A well-designed Colpitts oscillator can be utilized through the kHz range, up to approximately 130 MHz. Overtone operation is achieved by adding an inductive component in parallel with the emitter-ground capacitor. Common-emitter wiring will provide the best high frequency performance as it minimizes the effects of and variations in load characteristics. The transistor’s Miller capacitance also has a reduced impact in the common-emitter configuration.
COMMON-BASE OSCILLATORS

The common-base oscillator configuration is the most complicated to design. The version shown in Fig. 4 is designed for frequencies above 130 MHz, using crystals operating on and above the fifth overtone. As the name infers, it follows conventional common-base rules, providing mid-range voltage gain and sinusoid output. The operating frequency is set by the resonant frequency of the reactive components in the collector arm of the circuit. Output signal amplitude is adjusted by altering the ratio between capacitors on the output. Input impedance is low, a disadvantage at high frequencies (the in-circuit Q of the crystal is reduced). Medium output impedance characteristics allow it to drive a wide range of load devices.

The crystal operates in a series-resonant condition, requiring less gain margin from the amplifier. Since the crystal comprises the primary feedback path for oscillation, there is a resulting loss of loop gain from power diversion through its holder capacitance. This configuration is also more susceptible to stray, temperature, and component tolerance effects, as the inductive component is used to set the operating point instead of for band/mode trapping.

DESIGN & ANALYSIS

Historically, designing oscillators was accomplished through trial-and-error, with innumerable iterations of bread-boarding and testing. Now, with computerized circuit simulation, designers have the ability to be exacting in the design exercise - leaving bread-boarding as merely a final working model of their concept.

The key to reliable crystal oscillator design is concise analysis and circuit modeling under both open loop (without crystal) and closed loop (with crystal) conditions. Correlated with carefully measured data, this analysis aids in reducing breadboard iterations and increasing first-time accuracy. Physically, the key performance element is the interface between the crystal and circuitry. A well-designed and constructed interface produces a reliable oscillator.

There are two useful techniques for design and analysis of crystal oscillators. The first technique involves analysis and measurement of the gain and phase response of the circuit. A broad band analysis is performed with the crystal removed from the circuit to identify potential conditions for oscillation outside the intended frequency. A second broad band sweep with the crystal included is used to ensure the leads or holder capacitance are not inducing an undesirable response like an LC mode. A narrow band sweep is used to indicate proper conditions at the intended oscillation point. A well designed oscillator has a characteristically steep slope on the phase crossing at 0° or 360°, and a sufficient gain margin (i.e.: 2dB - see Fig. 5).

A steep phase slope and sufficient gain create an oscillator more resilient to change in frequency and output amplitude relative to temperature and voltage variations. For open loop gain phase analysis, a common method is opening the AC feedback loop, reflecting the impedance at the open point.

Fig 4: High frequency common base oscillator

Fig 5: Gain Pass Margin Illustration
The second analysis technique involves measuring negative resistance. In general, measurement becomes easier when one side of the crystal is tied to circuit ground, as with a basic Colpitts design. Offering practical advantages over the gain/phase technique, negative resistance facilitates a quicker one-port measurement for comparison with computer analysis. Accurate broad and narrow band negative resistance measurements on IC oscillators with a “floating” crystal (i.e: Pierce-type) are more difficult.

The fundamental strength of the negative resistance technique is its ability to analyze and measure the “real” impedance of the circuit and the crystal. The designer also needs a solid understanding of the crystal’s equivalent circuit parameters and their effect on the circuit. With these details in hand, it is a simple matter to measure the "imaginary" portion of the circuit and the crystal. By overlaying these four pieces of data the designer can predict whether or not the circuit will oscillate, where the circuit will oscillate, and what the design margins are.

The ability to closely correlate analytical versus measured data is no easy task. A solid understanding of active and passive devices and their equivalent circuits is required. A large volume of work and an understanding of key parameters is mandatory to develop computer models and techniques that accurately predict results. Once the models and measurement have been refined so theoretical data correlates with measured data, the designer has the tools necessary to decrease the burden and time required to design crystal oscillators.

Craig Taylor is the Chief Technical Officer for SaRonix LLC, an ISO9001 certified quartz crystal & oscillator designer and manufacturer that has supplied frequency control products since 1975. SaRonix supports its global customer base with engineering, sales and manufacturing facilities worldwide. For more information about this topic or frequency control products in general, local sales contacts, applications engineering support, or general corporate information, please visit the SaRonix web site at www.SaRonix.com or phone SaRonix at +1-650-470-7700 (800-227-8974), +31-314-375-959, or +65-363-8990.