Susceptibility of the Crystal Oscillator to Sinusoidal Signals over Wide Radio Frequency Range

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Abstract: Oscillators are sensitive to radio frequency interference. Therefore they can be applied to measure radio frequency interference. Radio frequency interference sources cover wide frequency ranges. It is interesting to see the frequency dependence of the oscillator susceptibility to radio frequency interference. This paper uses the crystal oscillator as the device under test and performs a systematic simulation on susceptibility. The transistor-level simulation shows that the oscillator susceptibility varies strongly with the signal frequency. The behavior of the oscillator susceptibility could be characterized with critical features and explained with three response modes. Both the simulated behavior and the proposed response mechanism are confirmed with the measurement results. The conclusion of the paper helps to calibrate oscillator sensors. It is also an important guideline for building analysis model in the design phase of the sensor.

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1. Introduction

Modern electronic systems generate signals and noises over a wide frequency range. One important range, typical for consuming electronics, automobiles, aircraft, communications, etc, is from sub-MHz to GHz [1]. Oscillators are widely applied in modern electronic systems. They are sensitive to radio frequency interference (RFI). That negative property can be utilized in a positive way. The oscillator can be applied to sense RFI.

Because RFI in the environment covers a wide frequency range, it is interesting to know reactions of the oscillator to RFI at different frequencies. If the sensitivity of the oscillator has strong variation along with the frequency, a troublesome procedure should be performed for the oscillator sensor. Designs of modern electronic devices, including sensors, normally requires a simulation verification before the device is sent to fabrication. The simulation requires model of the circuit. To complete the simulation within short time, the circuit model should be simplified. The degree of the simplification of the oscillator model depends on how complex the oscillator responses with RFI. Thus, the frequency response of the oscillator to RFI is important.

A few researches have been conducted on the response of the oscillator to sinusoidal signal [2-5]. However, those researchers have not provided the detailed frequency behavior of the oscillator susceptibility. [6] presents the response of the oscillator to interference. However, the frequencies of the interferences were below 1 KHz. [7, 8] studied the frequency behavior of the oscillator response in
MHz range. However, they used the parasitical effects in the package and the board to explain the frequency behavior. The response of the transistor circuits of the oscillator itself was neglected. This paper studies the frequency dependence of susceptibility of the oscillator itself: the behaviors and the mechanisms.

Section 2 examines the oscillator susceptibility from 0.5 MHz to 1 GHz through transistor level simulation. The paper distinguishes the two status of the oscillator: pass and fail. The threshold for the oscillator to transit from pass to fail is defined as the sensitivity. The criterion for failure determination is investigated by checking its effect on the simulation results.

Section 3 analyzes the simulation results. The geometry structure of the susceptibility-frequency curve is characterized with a few critical features. The behind response mechanisms for those features are investigated by watching the time-domain waveform of the oscillator at RFI frequency where those critical feature are located.

Section 4 explains the susceptibility measurement setup and shows the measurement results. The measured susceptibility is compared with the simulation result. To confirm the analysis in section 3, additional measurements are performed. The results are also compared with simulation. Section 5 concludes the whole paper.

2. Susceptibility Simulation

The device under test (DUT) is the crystal oscillator. The hardware prototype is the oscillator of a microcontroller [8]. In a microcontroller, the status of the oscillator can be monitored digitally: pass / fail. The oscillator contains the CMOS amplifier, the crystal resonator, and two foot-point capacitors. The amplifier is a single-stage common source amplifier biased at its amplified region by the on-chip feedback resistor. The input and the output of the oscillator are labeled with X1 and X2 respectively. A shaper is added to pin X1. The output of the shaper is the primary clock. The primary clock is supplied to the phase-locked loop (PLL). It is the PLL that monitors the status of the oscillator. The status of the oscillator can be read from a feedback signal of other pins of the microcontroller. The nature resonant frequency of the oscillator is fosc.

This paper assumes that the RFI is coupled with the input of the oscillator through capacitive channel. The frequency of the RFI is fRFI. RFI above certain intensity causes the failure of the oscillator. The PLL of the microcontroller monitors the primary clock. Once it cannot recognize the clock, the failure of the oscillator is detected.

To simulate the behavior of the oscillator, a transistor-level oscillator model is built and is shown in Fig. 1. It is a SPICE-type netlist. The amplifier is modeled with transistors and resistors. The shaper is a Schmitt trigger. It is also modeled with transistors.

The crystal model is a RLC netlist. CX1 and CX2 represent the two foot-point capacitors. The RFI source is modeled with a voltage source (VRFI) and an internal resistance (RS). CINJ is the coupling capacitance. In this case, according to [9], fosc is selected to be 8 MHz; CX1 and CX2 are both 15 pF. CINJ is 6.8 pF. Transistors models follow SMIC 130 nm CMOS technology. The simulator is HSPICE from Synopsys. fRFI range from 0.5 MHz to 1 GHz is simulated. VRFIX is the RFI voltage between X1 and the ground. The susceptibility is determined by the minimum VRFIX under which the oscillator fails. It is labeled with VRFIXM. Obviously, high VRFIXM corresponds to low susceptibility. In case of causing confusion, this paper uses VRFIXM to indicate the susceptibility.
value from 5% to 20%, which is already 4 times spaced, brings only 20% change on the simulation result in the low frequency range while almost no change in the high frequency range. Obviously, the simulation results are not sensitive to the margin. Therefore, a moderate value can be selected for the margin for the susceptibility simulation for simulation-measurement comparison.

Fig. 2. Frequency response of the oscillator susceptibility, simulation results.

3. Susceptibility Analysis

With reference to Fig. 2, the susceptibility presents a strong dependence on $f_{\text{RFI}}$. The susceptibility curve contains three regions:

- **Region FR1**: The region is up to $f_{\text{OSC}}$. The sensitivity curve is relatively flat, indicating that the susceptibility varies with the frequency in a weak way.

- **Region FR2**: The region is around $f_{\text{OSC}}$. In the center of the region is a peak. The susceptibility varies strongly with the frequency.

- **Region FR3**: The region is located well above $f_{\text{OSC}}$. The region contains drops. The whole region has sensitivity considerably lower than FR1 and FR2. The susceptibility varies with the frequency at large amplitude.

- Besides those three regions, there is a fourth region close to 1 GHz.

The differences in behaviors of the susceptibility in those three regions indicate that the response mechanisms of the oscillator to RFI in those regions are different. To find those mechanisms, the time domain waveforms of the primary clock signals under RFI with various $f_{\text{RFI}}$ are simulated and are depicted in Figs. 3, 4 and 5. $f_{\text{RFI}}$ of 1 MHz (as representative of FR1), 8 MHz (as representative of FR2), and 100 MHz (as representative of FR3) are taken into simulation. It is also noted that simulations on other $f_{\text{RFI}}$ show the same type of behavior as one of the depicted three cases. It is obvious that the signal of the primary clock responds in a quite different way to RFI with different frequencies.

Fig. 3. Response of the oscillator to RFI at 1 MHz, simulation results.

Fig. 4. Response of the oscillator to RFI at 8 MHz, simulation results.

Fig. 5. Response of the oscillator to RFI at 100 MHz, simulation results.

In Fig. 3, when the $f_{\text{RFI}}$ is low and is inside the gain window of the amplifier, the response of the primary clock signal shows that some clock pulses disappear, leaving just tiny tips. This vanish of pulse occurs periodically and comes up with both positive and negative pulses. With the disturbance getting
stronger, more pulses in the time axis disappear. It is interesting that the disappearance of adjacent positive pulses actually forms a larger negative pulse, vice versa. Finally, with continuous enhancement of the RFI, working primary clock signals will be totally distorted and replaced by the signals which oscillate at the frequency of \( f_{\text{RFI}} \) rather than \( f_{\text{OSC}} \). The response mode in this case is called oscillation competition. The RFI oscillation competes with the nature oscillation.

In Fig. 4, when the \( f_{\text{RFI}} \) is almost identical to \( f_{\text{OSC}} \), sequences of clock pulses disappear and leave only several tiny tips. We call the time when pulses disappear continuously as the pulse-vanishing-duration (PVD). The PVD of the pulses under \( V_{\text{RFI}} = 1.8 \, \text{V} \) is shown in 5 \( \mu \text{s} \) and 3 ms timescales so that a more clear picture of this waveform behavior can be seen. It is clear that the PVD appears periodically under RFI and the gap enlargers with the increase of the \( V_{\text{RFI}} \). The response mode is called coherent coupling. The RFI oscillation and the nature oscillation interfere coherently with each other. They cancel each other and thereby form PVD.

In Fig. 5, when the \( f_{\text{RFI}} \) is high and is outside the gain window of the amplifier, the primary clock signal is basically normal under weak RFI, except that there are some ripples (which are RFI signal rather than contracted pulses) on the top and some tips on the bottom of the clock pulses. With an even higher \( V_{\text{RFI}} \), the oscillating clock signal disappears quickly, and leaves only a noisy voltage at the supply voltage level. The response mode is called gain absorption. The RFI eats up the gain of the amplifier for the nature oscillation. However, it does not replace the nature oscillation. One thing worth mentioning here is that the RFI level causing the failure of the oscillator in FR3 is considerably lower than that in FR1 and FR2.

The above analysis shows clearly that the response of the oscillator to RFI follows three modes. Each mode dominates the behavior in the corresponding frequency range. That is why the oscillator susceptibility has such strong dependence on the frequency of the incoming signal.

4. Susceptibility Measurement

Two types of the measurements are performed. The first measurement is to verify three different regions in the simulated susceptibility curve. The second measurement is to verify the corresponding response mode.

The susceptibility curve is measured according to the Direct Power Injection (DPI) method [1]. It is now an IEC standard (standard no. 62132). The setup is depicted in Fig. 6. The DUT is packaged and mounted on a board. RFI signals are generated, amplified and coupled to the \( X_1 \) pin of the DUT. An oscilloscope is employed to detect a feedback signal from a particular pin of DUT. A program is running inside the microcontroller to monitor the status of the oscillator module. In the normal operation, the microcontroller will generate a square wave feedback signal, which falls inside the tolerance mask on the oscilloscope. Once an oscillator error is found, the feedback signal will be irregular. Therefore, by comparing the feedback signal and the mask on the oscilloscope, the failure of the oscillator can be detected by oscilloscope and is known by the center “computer”. The center computer runs a test program controlling the RFI source and the oscilloscope. During susceptibility measurement, \( f_{\text{RFI}} \) is swept from 0.5 MHz to 1 GHz. At each \( f_{\text{RFI}} \), the amplitude of RFI is increased from a low level to a level which causes the oscillator to fail. Once failure is detected the computer will record the power of the RFI and the corresponding \( f_{\text{RFI}} \).

The measurement result is shown in Fig. 7. To compare the measurement and the simulation, the simulation result (margin = 20 \%) is drawn in the low part of Fig. 7. The vertical axis of the measurement result is the minimal forward power where the oscillator fails.

It is difficult to measure the voltage amplitude of RFI at the \( X_1 \) pad, therefore the forward power (\( P_{\text{RFI}} \)) is measured. Obviously, both high \( P_{\text{RFI}} \) and high \( V_{\text{RFI, XM}} \) indicate that the oscillator has a low susceptibility. The relationship between \( P_{\text{RFI}} \) and the susceptibility is similar to the relationship between \( V_{\text{RFI, XM}} \) and the susceptibility. The comparison between those two curves reasonably reflects the comparison of the simulated and measured susceptibility. The measured susceptibility also shows the three regions: flat, peak, and drop at the same locations. The measurement results and the simulation results are well correlated. It is a strong support to the three-region characterization.
The peak at above 500 MHz, corresponding to the fourth region in the simulation section, is due to resonances of the crystal and the foot-point capacitors [7]. It is not in the scope of this paper.

5. Response Measurement

The simulation section presents the time-domain waveforms in the three regions. Response modes are raised based on those simulation results. It is interesting to verify the simulated behavior with measurement. Therefore a set of waveform measurements are performed. To measure the primary clock is difficult, because the output of the shaper is located inside the chip. However, the primary clock is the shaped version of the X1 signal. Therefore the waveform on X1 can be used to analyze the response mechanism.

Fig. 8 presents the waveform of X1 when there is no RFI. It is a pure single frequency sinusoidal signal. With the time scale in the right left of the picture, the oscillation frequency of 8 MHz can be identified.

Fig. 9 presents the waveform of X1 and X2 where fRFI is located in region FR1. The yellow curve is the signal of the “clock_out” pin of the microcontroller. When PRFI reaches 15 dBm, the clock signal disappears, which indicates oscillator fails. Checking the waveform at X1, we see a small amplitude oscillation at 1 MHz (attention to the time scale). The signal X2 confirms the 1 MHz oscillation. Fig. 9 shows clearly that when the intensity of RFI is sufficiently high, the RFI oscillation replaces the nature oscillation. The behavior here is consistent with the observation in the corresponding simulation in section 3.

Fig. 10 presents the X1 waveform while fRFI is located in FR2. To see the PVD, a large time scale of 50 μs is used here. The RFI oscillation is mixed with nature oscillation coherently. RFI cancels the nature oscillation in certain regions and enhances the later in other regions. Obviously the cancellation will cause the absence of the clock pulses at the output of the shaper. Again, the behavior is consistent with the observation in the corresponding simulation.

Fig. 11 presents the waveform where fRFI is located in region FR3. The forward power of RFI is only 0 dBm. However, the oscillation in X1 is almost unobservable at that weak RFI. The nature oscillation disappears. But the RFI has not taken the role of oscillation. There is only a small 100 MHz ripple there. The X1 signal stays at low voltage which will make the output of the shaper always high. The “clock_out” signal stays still. The RFI forward power in Fig. 9 is 15 dBm and in Fig. 10 is 25 dBm. 0 dBm
is much lower than both of them. The measurement shows clearly that very low leveled RFI can already stop the nature oscillation. The behavior is again consistent with the observation in the corresponding simulation.

The function simulation during the design phase of the oscillator sensor should either employ a transistor-level circuits or at least a susceptibility-frequency curve as the oscillator model. If later option is taken, a parameter extraction should be performed to obtain the curve. The strong frequency response of the oscillator greatly increases the simulation effort.

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