Analysis and Improvement of Oscilloscope Jitter Measurement Floor Based on Simulation Experiments

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Abstract: Oscilloscopes are crucial universal instruments in the fields of electronic information and communication, capable of making time-domain measurements of signals and systems. Due to imperfect hardware, oscilloscopes exhibit a certain jitter. This paper refers to the jitter originating from the oscilloscope itself is called the oscilloscope jitter measurement floor. During the process of measuring signal jitter using an oscilloscope, the jitter measurement floor inevitably affects the measurement results, introducing errors. This paper primarily investigates factors influencing the oscilloscope jitter measurement floor, including the oscilloscope’s sampling clock jitter, inherent noise, and input signal frequency，etc.. Simultaneously, the impact of these factors on oscilloscope measurement results is assessed, and experimental verification is conducted using an oscilloscope simulation platform. Finally, methods for reducing the oscilloscope jitter measurement floor are proposed.

1 INTRODUCTION

The definition of jitter varies slightly across different fields, leading to inconsistencies in the definitions provided by international organizations and institutions such as the International Electrotechnical Commission (IEC), Institute of Electrical and Electronics Engineers (IEEE), and American National Standards Institute (ANSI), etc.(Std, I.-Peterich, D.),. This paper adopts the latest standard for defining jitter as provided by IEEE in 2020, i.e., jitter is the deviation between the actual time of a set of events and their ideal values (Std, I., Zhu Jiangmiao).

Jitter is a measure of short-term uncertainty in the time domain of a signal and is assessed using phase noise in the frequency domain to measure the short-term instability of the signal. Oscilloscopes are indispensable for time-domain measurement and analysis of signals. However, due to the presence of oscilloscope jitter measurement floor, the measured jitter results inevitably contain errors other than the signal jitter. If the signal jitter is significantly greater than the oscilloscope jitter measurement floor, then these errors can be neglected. However, if the above requirement is not met, the oscilloscope jitter measurement floor will cause significant errors, thereby affecting the accuracy of the measurement results. Therefore, it is of great importance to identify the factors contributing to the oscilloscope jitter measurement floor, understand how these factors affect the measurement results, and minimize their impact in order to study oscilloscope measurement.

Oscilloscopes can be categorized as analog oscilloscopes and digital oscilloscopes. With technological advancements, analog oscilloscopes have been gradually replaced by digital oscilloscopes, and digital oscilloscopes can further be classified into sampling oscilloscopes and real-time oscilloscopes. Sampling oscilloscopes are also known as communication signal analyzers. However, whether it is a sampling oscilloscope or real-time oscilloscope, the components such as analog-to-digital converter (ADC), attenuators and amplifiers in the analog front-end, are vital for their operation.

The primary sources contributing to the oscilloscope jitter measurement floor are the sampling clock jitter in the ADC, oscilloscope's analog front-end and digital processing. On the basis of clarifying how the above factors affect the oscilloscope jitter measurement floor is crucial for effectively reducing their impact on the measurement results.

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2 SAMPLING PRINCIPLE OF SAMPLING OSCILLOSCOPE

An oscilloscope is an electronic instrument that converts electrical signals, primarily voltage, into visible traces on a display screen. In other words, an oscilloscope can convert electrical signals into optical signals and dynamically plot the electrical signals in a two-dimensional form over time. The voltage is plotted on the vertical axis of the oscilloscope display screen, while the time is plotted on the horizontal axis. The plotted voltage and time are ultimately displayed as a graph of the input signal, often referred to as a "waveform". As the characteristics of the input signal change, the displayed waveform on the oscilloscope screen is continuously updated.

The bandwidth range of a sampling oscilloscope is much wider than that of a real-time oscilloscope, meaning it can measure signals with a broader bandwidth range. Due to the high frequency of the input signal, the oscilloscope does not directly display the measured signal. Instead, it uses a frequency-conversion method to sample the signal at different positions in the waveform of the measured signal, using a time much shorter than the period of the measured signal. The sampling is performed sequentially in a stepped order for each waveform of the signal (Wang Shibiao).

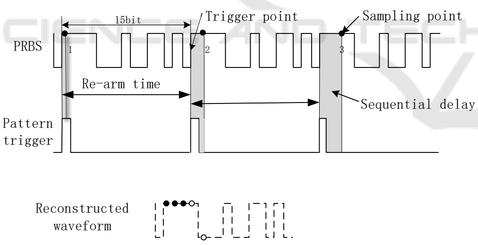


Fig. 1. Schematic diagram of sampling principle of sampling oscilloscope-

Taking PRBS code as an example, Fig 1 illustrates the sampling principle of a sampling oscilloscope. A trigger point is provided by a pattern trigger from the clock signal, and sampling is performed after the trigger. After each pattern trigger, new sampling is carried out at sampling points slightly away from the pattern trigger point and repeated. Then, the sampled oscilloscope reconstructs the waveform. This paper focuses on studying the jitter of sampling oscilloscopes, and the oscilloscopes mentioned following the paper refer to digital sampling oscilloscopes unless otherwise specified.

3 SAMPLE CLOCK JITTER

The sampling clock is an essential part of ADC. The sampling oscilloscope through the ADC to sample the input signal, and then converting each sample point of the analog signal into a digital value. The sampling clock controls when the ADC performs the sampling. In other words, the frequency of the sampling clock determines the time interval of the oscilloscope. However, the clock signal generated by the sampling clock itself exhibits a certain jitter, which is referred to as clock jitter. Clock jitter is an inherent characteristic that cannot be completely eliminated (S. Huang) and is one of the main sources of the oscilloscope jitter measurement floor.

Clock jitter can be classified into random jitter and deterministic jitter. Random jitter is caused by thermal noise, flicker noise, and shot noise, which are related to the electronic and hole characteristics of electronic and semiconductor devices. The sources of deterministic jitter are switching power supply noise, crosstalk, and electromagnetic interference, etc., which are related to circuit design (LI Liping, Zhang Changjun).

Clock jitter can be represented in various ways (Zhu Jiangmiao), such as Period jitter (PEJ), Cycle to Cycle jitter (C2C), and Timing Error (TE). In this paper, TE is used to represent clock jitter, which refers to the deviation between the actual edge of the clock and the ideal edge. Fig 2 gives the schematic diagram of TE.

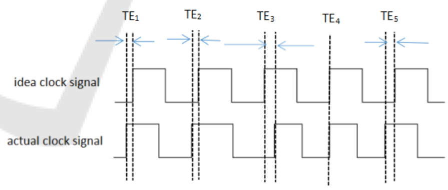
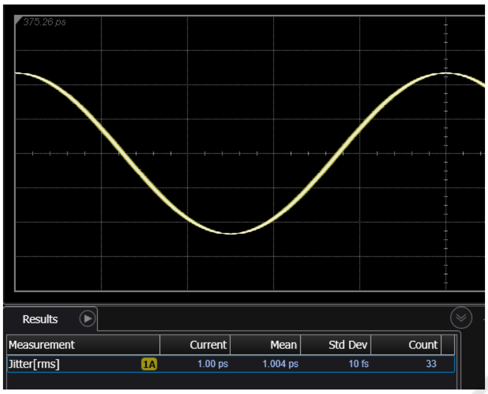
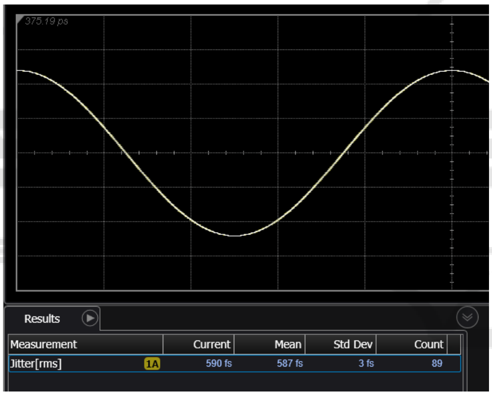


Fig. 2. Schematic diagram of TE in clock jitter.

Due to the high sampling clock frequencies of modern high-bandwidth oscilloscopes, which can reach up to 160G/s or higher, the time interval between samples is very small. Therefore, ensuring that each actual sample point falls at the ideal position is challenging. In other words, the existence of clock jitter causes the sampled amplitude of the signal to not correspond exactly to its actual sampling time, thereby affecting the measurement results of the oscilloscope. Since clock jitter includes both deterministic jitter and random jitter, averaging multiple waveforms can effectively remove the random jitter in clock jitter, reducing the magnitude of clock jitter. Fig 3 illustrates the impact of clock jitter on the measurement results through simulation experiments. In the figure 3, a represents the input signal measured by the oscilloscope without waveform averaging, and b represents the input signal measured by the oscilloscope with waveform averaging.



a)



b)

Fig. 3. Schematic diagram of measurement results with and without clock jitter.

Therefore, to ensure that the deviation between the actual sampling time and the ideal sampling time of each sampling point instant, i.e. TE, as small as possible, is a critical task to improve the measurement accuracy of the oscilloscope. However, regardless of technological advancements, the jitter value will never be zero due to the inherent characteristics of the hardware equipment.

4 INHERENT NOISE

The noise in the analog front-end and digital processing of an oscilloscope is also one of the sources of jitter measurement floor, which is referred to as inherent noise in this article. In addition to introducing amplitude measurement errors, the inherent noise of an oscilloscope can also cause changes in the threshold crossing time of the signal, resulting in jitter (M. Shimanouchi, 2001).The schematic diagram illustrating the specific impact of inherent noise on jitter measurement floor is shown in Figure 4. Next, we will separately discuss the noise in the digital processing of the oscilloscope and the noise generated by the analog front-end.

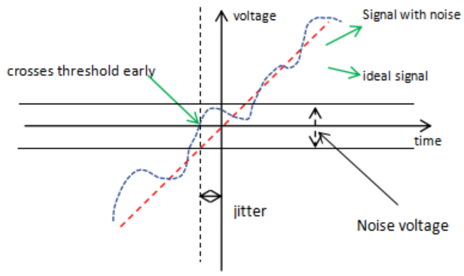


Figure 4: Schematic diagram showing the impact of noise on jitter measurement floor.

4.1 Quantization Noise

Quantization error in the digital processing of an oscilloscope is also known as quantization noise, which is introduced by the oscilloscope's analog-to-digital converter (ADC) and is mainly related to the resolution and performance of the ADC.

According to the principles of sampling and quantization in a sampling oscilloscope, the resolution of the ADC chip directly determines the vertical sampling accuracy of the oscilloscope. For example, if the ADC conversion chip is 8-bit, the vertical signal can be divided into 256 segments and then quantized. Assuming the input signal amplitude is 1V, the quantization accuracy is 1V/256, which means the ADC can only distinguish voltage signals greater than 1/256V. if the ADC conversion chip is 10-bit, the vertical signal can be divided into 1024 segments, and keep the input signal amplitude still at 1V, the quantization accuracy becomes 1V/1024, meaning the ADC can distinguish voltage signals greater than 1/1024V. It can be seen that the higher the number of bits of the ADC chip in the oscilloscope, the higher the vertical resolution and the smaller the quantization noise of the oscilloscope. However, for the same oscilloscope, the number of quantization bits is generally constant, and therefore its quantization noise is also fixed.

4.2 Noise Generated by the Analog Front-End of the Oscilloscope

The noise generated by the analog front-end of the oscilloscope is mainly caused by the attenuator and the preamplifier. The analog-to-digital converter (ADC) cannot distinguish between signal and noise during sampling, so when the signal is amplified, the noise will also be amplified. The amplification factor of the attenuator and preamplifier is not fixed, resulting in the variability of this noise.

The attenuator and preamplifier of the oscilloscope can be used to control and adjust the vertical sensitivity of the oscilloscope, which is an important component in the front-end circuit of the oscilloscope, allowing users to select different sensitivity ranges for the signal to accommodate input signals with different amplitudes. Therefore, the vertical sensitivity setting of the oscilloscope and the amplitude of the input signal can affect the noise generated by the analog front-end of the oscilloscope and then affect the jitter measurement floor. To verify this conclusion, this article uses simulation experiments to verify the influence of vertical sensitivity setting and input signal amplitude on the jitter measurement floor.

1) Influence of Vertical Sensitivity on jitter measurement floor

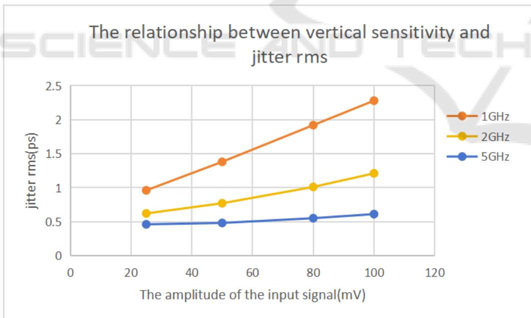


Figure 5: Relationship between vertical sensitivity and jitter rms.

First, a sinusoidal signal with a jitter value of 400 fs is inputted into the simulation software. In the case of other parameters remain unchanged, the vertical sensitivity is adjusted and the number of measuring result (jitter rms) at different vertical sensitivities are recorded. To avoid experimental variability, multiple signals with different frequencies are tested, and multiple sets of data are recorded and plotted. As shown in Figure 5, regardless of the change in signal frequency, the oscilloscope's jitter measurement results decrease as the vertical sensitivity increases. It should be noted that a higher numerical value of the vertical sensitivity indicates lower sensitivity. As the vertical sensitivity decreases, the oscilloscope measurement results increase. However, the input signal jitter remains unchanged, indicating that the jitter measurement floor of the oscilloscope is increasing, and the trend is consistent with the change in the measured results in Figure 5.

When the vertical sensitivity decreases, the noise increases, resulting in an increase in the jitter measurement floor of the oscilloscope. Therefore, when using an oscilloscope to measure a signal, it is advisable to fill the waveform on the oscilloscope screen as much as possible to reduce the jitter measurement floor.

2) Influence of Input Signal Amplitude on jitter measurement floor

To investigate the influence of input signal amplitude on the jitter measurement floor of the oscilloscope, the vertical sensitivity of the oscilloscope is kept constant while changing the input signal amplitude. Experimental data is recorded and plotted. As shown in Figure 6, it can be observed that under the condition of constant vertical sensitivity, the smaller the signal amplitude, the larger the jitter measurement result of the oscilloscope. Similarly, the input signal jitter remains unchanged. This indicates that the jitter measurement floor increases. This is because the smaller the signal amplitude, the larger the amplification factor, and the more severe the effect of noise. However, this does not mean that a larger signal amplitude is always better, as once the signal amplitude exceeds the measurement range of the oscilloscope, the measurement result will be invalid.

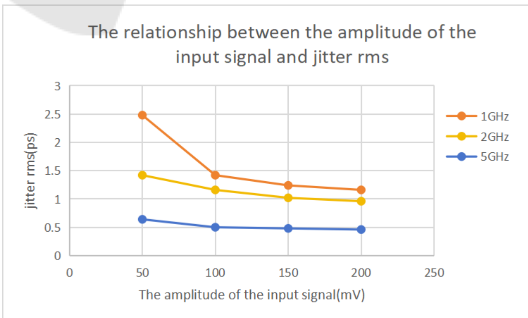


Figure 6: Relationship between the amplitude of input signal and jitter rms.

In conclusion, the inherent noise of an oscilloscope mainly consists of the two factors mentioned above. The quantization noise is fixed for a given oscilloscope, while the impact of oscilloscope analog front-end noise on jitter is related to the vertical sensitivity and input signal amplitude of the oscilloscope. A higher vertical sensitivity setting of the oscilloscope results in a smaller noise, and vice versa. Within the measurement range of the oscilloscope, a larger input signal amplitude leads to a smaller noise. Therefore, when measuring the input signal, the vertical sensitivity of the oscilloscope can be adjusted to make the vertical sensitivity as large as possible when the signal is displayed completely on the oscilloscope.

5 INPUT SIGNAL FREQUENCY

In addition to the factors mentioned above, the frequency of the input signal during actual measurement will also have an impact on jitter. By keeping the input signal jitter and vertical sensitivity constant, the frequency of the input signal is changed, and the measurement results are recorded. Figure 7 shows the relationship between input signal frequency and measurement results of oscilloscope in the simulation experiment.

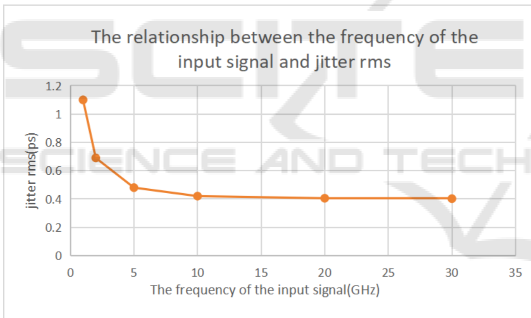


Figure 7: Relationship between the frequency of input signal and jitter rms.

According to Figure 7, it can be observed that as the input signal frequency increases, the jitter measurement results (jitter rms) of the oscilloscope decrease. This is because the higher the frequency of the input signal, the faster the signal conversion rate, and the less the impact of noise superimposed on the time axis. The specific impact is illustrated in Figure 8. In other words, the influence of inherent noise on the measurement results decreases with higher input signal frequency. This also demonstrates the effect of the oscilloscope's inherent noise on the jitter measurement floor.

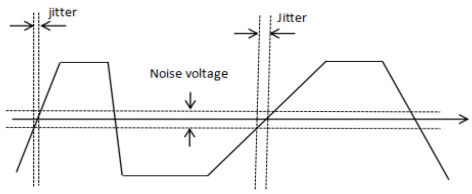


Figure 8: Schematic diagram of the impact of signal slope on jitter measurement floor.

6 CONCLUSION

Based on the theoretical analysis and simulation studies, we can conclude that the jitter measurement floor of an oscilloscope is affected by the oscilloscope's sampling clock jitter, inherent noise, and input signal frequency. The sampling clock jitter is beyond the control of users, thus the oscilloscope manufacturers require continuous optimization of its circuit design and hardware equipment to minimize its jitter value. The quantization noise in the inherent noise of an oscilloscope is related to the resolution of the ADC conversion chip. Higher resolution leads to smaller quantization errors, which is also the reason why many oscilloscope manufacturers have been continuously improving the ADC resolution in recent years.

It can be verified by experiments that the analog front-end noise in the inherent noise, under the condition of constant input signal, is closely related to the vertical sensitivity setting of the oscilloscope and the input signal frequency. In many cases, the impact of analog front-end noise on jitter measurement floor is much greater than other factors. Therefore, selecting the appropriate vertical sensitivity during the measurement process is one of the important means to reduce the oscilloscope jitter measurement floor. After reducing the jitter measurement floor, its contribution to the oscilloscope measurement results will correspondingly decrease.

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