

# APPLICATION NOTE

## **AN219**

A metastability primer

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## INTRODUCTION

When using a latch or flip-flop in normal circumstances (i.e., when the device's setup and hold times are not being violated), the outputs will respond to a latch enable or clock pulse within some specified time. These are the propagation delays found in the data sheets. If, however, the setup and hold times are violated so that the data input is not a clear one or zero, there is a finite chance that the flip-flop will not immediately latch a High or Low, but get caught half way in between. This is the metastable state, and it is manifested in a bi-stable device by the outputs glitching, going into an undefined state somewhere between a High and Low, oscillating, or by the output transition being delayed for an indeterminable time.

Once the flip-flop has entered the metastable state, the probability that it will still be metastable some time later has been shown to be an exponentially decreasing function. Because of this property, a designer can simply wait for some added time after the specified propagation delay before sampling the flip-flop output so that he can be assured that the likelihood of metastable failure is remote enough to be tolerable. On the other hand, one consequence of this is that there is some probability (albeit vanishingly small) that the device will remain in a metastable state forever. The designer needs to know the characteristics of metastability so that he can determine how long he must wait to achieve his design goals.

## THE CHARACTERISTICS OF METASTABILITY

In order to define the metastability characteristics of a device, three things must be known: first, what is the likelihood that the device will enter a metastable state? This propensity is defined by the parameter " $T_0$ ". Second, once the device is in a metastable state, how long would it be expected to remain in that state? This parameter is tau ( $\tau$ ) and is simply the exponential time constant of the decay rate of the metastability. It is sometimes called the metastability time constant. The final parameter is the measured propagation delay of the device. Commonly, the typical propagation delays found in the databook are used for this, and it is designated "h" in the equations (although most designers are familiar with this value as  $T_{PD}$ ). Now let's see how  $\tau$  and  $T_0$  are determined by measurements.

## A TEST METHOD

Suppose we wanted to measure the metastability characteristics of a fictitious edge-triggered D-type flip-flop and we had a test system that would count each time the flip-flop is found in a metastable state at some time after a clocking edge. The first thing we would like to know about the flip-flop would be the "h" or typical propagation delay. We could measure the delay or look it up in the databook (of course, measuring the actual delay would allow more precise results). this fictitious flip-flop has an h of 7ns. In this test we decide to use a clock frequency of 10 MHz. This frequency is primarily a function of the test system's ability to assimilate the information. The data will run at 5MHz asynchronously to the clock and with a varying period. This frequency was chosen because at two transitions per cycle, the data signal produces 10 million points each second where it is possible for the flip-flop to go into a metastable state, an average of one point for each clock pulse. An important point about the characteristic of the data signal in relation to the clock is that the data transitions must have an equal probability of occurring anywhere within the clock period or the results could be skewed. In other words, we need to have a uniform distribution of random data transitions (High and Low) relative to the clocking edge.

The first measurement we take is to determine the number of times the device is still in a metastable state 8ns after the clock edge. With this device there are 792 failures after 1 billion clock cycles. Changing the time to 9ns, we measure 65 failures after another 1 billion cycles. Because metastability resolves as an exponentially decaying function, the two points define the exponential curve and they can be plotted as shown in Figure 1. An equivalent plot can be made using a semilog scale as in Figure 2. The slope of the line drawn through the two points represents  $\tau$ . with these two points the  $\tau$  can be determined by equation (1):

$$(1) \quad \tau = \frac{t_2 - t_1}{\ln(N_1/N_2)}$$

where  $N_1$  and  $N_2$  are the number of failures at times  $t_1$  and  $t_2$ , respectively.

Working through the numbers gives us a  $\tau$  of 0.40ns.  $\tau$  of this order is representative of the FAST line of flip-flops.

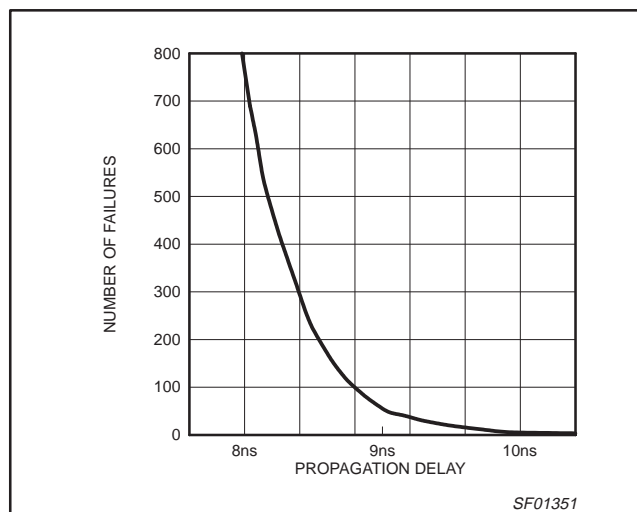


Figure 1. Exponential Decay of Failures

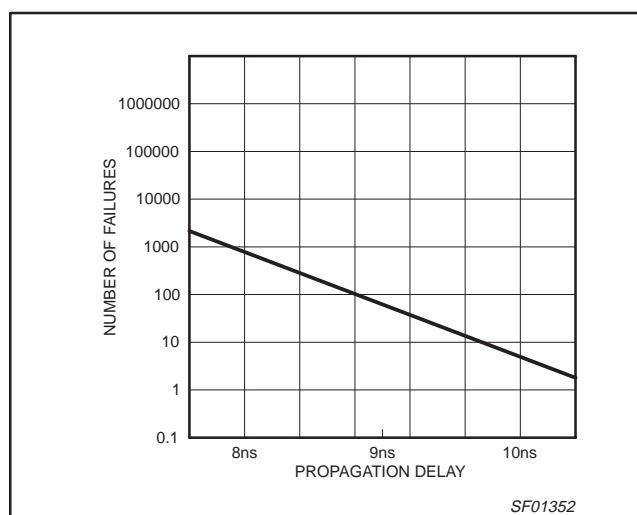


Figure 2. Semi-Log Graph of Failures

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Earlier we stated that  $T_0$  is an indicator of the likelihood that the device will enter a metastable state. Now we will attempt to explain it. At 9ns after the clock, we observed 65 failures in 1 billion clock cycles. Since the data transits on average once per clock cycle and the period of this clock is 100ns, from equation (2) we can say that there appears to be an aperture about 0.0065 picoseconds wide at the input of the device that allows metastability to occur for 9 or more nanoseconds. Another way of explaining the same thing would be to suppose that if 1 billion data transitions were uniformly and randomly distributed over a clock period of 100ns, you would expect 65 of these transitions to cause the outputs to go into a metastable state and remain there for at least 9ns.

$$(2) \quad T_9 = \frac{N_9 P_C}{N_{C9}}$$

Where  $N_{C9}$  is the number of clocking events at 9ns (in this instance, 1 billion),  $P_C$  is the period of the clock, and  $N_9$  is the number of failures recorded at 9ns.

By the same reasoning, the window at 8ns appears to be 0.0792 picoseconds wide. It seems to have grown because there are, of course, more failures after 8ns than after 9ns. This aperture

has been normalized by researchers to indicate the effective size of the aperture at the clock edge, or time zero. Unfortunately, the normalization process tends to obscure the interpretation of  $T_0$ .  $T_0$  can be calculated using equation (3). Figure 2 is an extension of Figure 2 and shows the relationship of  $T_0$ ,  $h$ , and  $\tau$ .

$$(3) \quad T_0 = T_8 e^{\left(\frac{8\text{ns}}{\tau}\right)}$$

or equivalently,

$$T_0 = T_9 e^{\left(\frac{9\text{ns}}{\tau}\right)}$$

In this case  $T_0$  is 38.4 microseconds and this value is again typical of the FAST line of products.

Figure 3 is an extension of Figure 2 and gives a graphic indication of  $T_0$ . The number of failures plots on the same scale as the aperture size but the number of failures is dependent on the number of clock cycles used in the test (we always used 1 billion in this paper) and the ratio of data transitions to clock pulses (1:1 in this paper). On the other hand, the aperture size is independent of these things.

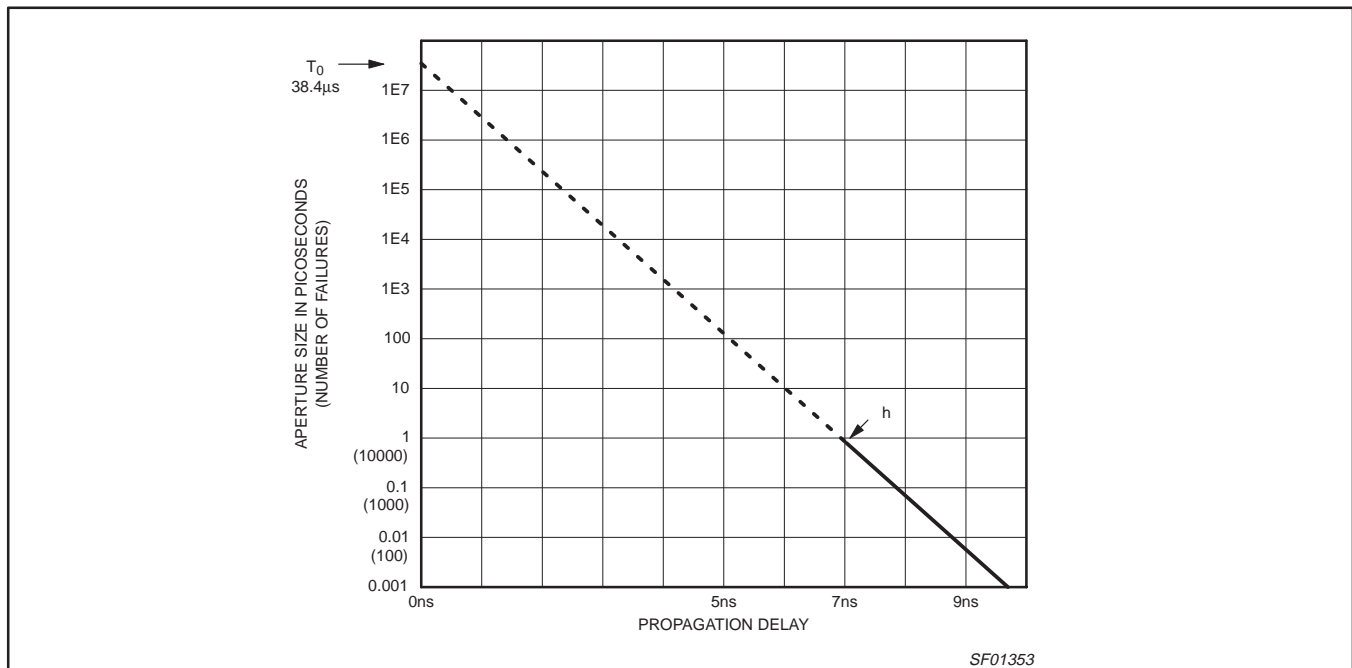


Figure 3. Extended Semi-Log Graph

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## MTBF

Having determined the  $T_0$  and  $\tau$  of the flip-flop, calculating the mean time between failures (MTBF) is simple. Suppose a designer wants to use the flip-flop for synchronizing asynchronous data that is arriving at 10MHz, he has a clock frequency of 25MHz, and has decided that he would like to sample the output of the flip-flop 15ns after the clock edge. He simply plugs his numbers into equation (4).

$$(4) \quad \text{MTBF} = \frac{e^{\left(\frac{t'}{\tau}\right)}}{T_0 f_C f_i}$$

In this formula,  $f_C$  is the frequency of the clock,  $f_i$  is the average input event frequency, and  $t'$  is the time after the clock pulse that the output is sampled (of course  $t' > h$ ). In this situation, the  $f_i$  will be twice the data frequency because input events consist of both Low and High data transitions. For the numbers above, the MTBF is one million seconds, or about one failure every 11.6 days. If the designer would have tried to sample the data after only 10ns, the MTBF would have been 3.8 seconds.

Metastability literature can be very confusing because several companies use different nomenclature and often the fundamental parameters are obscured by scale factors, so it is important that the user understand MTBF. Let's try a thought experiment to determine the correct MTBF formula. We know the size of the aperture at 8ns, so we need to know how often that window will occur. This is supplied by the clock period. This gives a ratio of window size to clock period and gives us the likelihood of a transition within the clock period causing a metastable state that lasts beyond the 8ns point. Now we need to know the number of input events per clock period to determine the MTBF at 8ns. This is supplied by the average input event period and produces the equation below where  $P_C$  and  $P_i$  are the periods of the clock and input events, respectively.

$$(5) \quad \text{MTBF} = \frac{1}{T_8 \frac{1}{P_C} \frac{1}{P_i}} = \frac{1}{T_8 f_C f_i}$$

This gives the MTBF for 8ns, but how can the formula be developed to handle other times? It has been stated in this paper that the rate of decay of metastable events is an exponential function with a time constant of  $\tau$ . Using this information gives the equation below, where  $t'$  is the time after the clock pulse that the output is sampled.

$$(6) \quad \text{MTBF} = e^{\left(\frac{t' - 8\text{ns}}{\tau}\right)} \frac{1}{T_8 f_C f_i} = \frac{e^{\left(\frac{t'}{\tau}\right)}}{T_8 e^{\left(\frac{8\text{ns}}{\tau}\right)} f_C f_i} = e^{\left(\frac{t'}{\tau}\right)} \frac{1}{T_0 f_C f_i}$$

A point should be made here about MTBF. This is the mean time between failures, and as such, does not indicate the average time between failures. In fact, in this situation, the MTBF is the time before which there is a 63.2% probability that a failure would have occurred. Suppose a device has a MTBF of one million seconds like the example above; because the MTBF is an exponential function, there is a 9.5% probability that a failure will occur in the first 1.16 days of operation. This might cause the user to feel that the device is failing more than expected. The user would find that 50% of his failures would occur within 8 days. Figure 4 gives a visual interpretation of this idea: time constant one represents one million seconds, in this case.

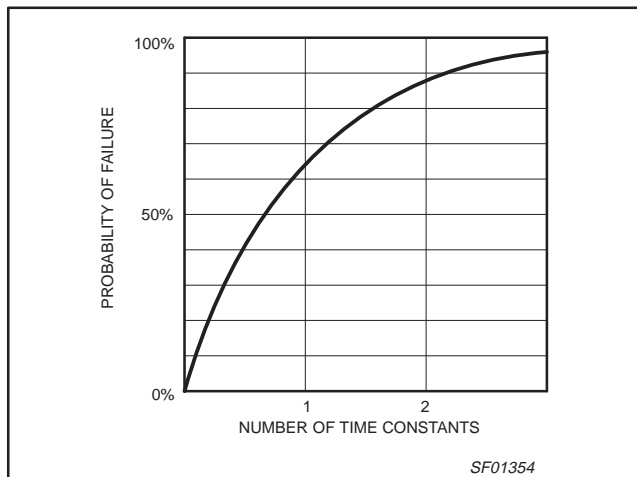


Figure 4.

## RECENT DEVELOPMENTS

The quest for better metastability characteristics in flip-flops has recently resulted in the development of flip-flops with  $\tau$ s significantly less than 0.40ns. Perhaps the most notable of these is the Philips Semiconductors 74F50XXX series with typical  $\tau$ s of 135ps. The specifications of these new products can cause confusion among the uninitiated because the typical  $T_0$  on these devices is 9.8 million seconds, or about 113 days. This is an example of how the normalization process obscures the interpretation of  $T_0$ . In the newest products, the  $\tau$ s have decreased faster than the normal propagation delays primarily due to speed limitations of the outputs.

Using the example above, and calculating  $T_7$  from equation (3) we see that the window at  $h$  is 0.965ps. Now let's assume that we have a device with the same size window (0.965ps) at  $h$ , and an  $h$  of 7ns. The difference between this device and the previous example is that this device has a  $\tau$  of 150ps. clearly, if the device has the same  $h$  and the same size of window at  $h$  but a smaller  $\tau$ , the device is better. But let's calculate the  $T_0$ .

$$(7) \quad T_0 = T_7 e^{\left(\frac{7\text{ns}}{\tau}\right)}$$

$$T_0 = 178 \text{ million seconds!}$$

Comparing the  $T_0$  of any two devices does not show which device is superior. However, one can expect that the device with the lower  $\tau$  is superior in all but the most peculiar circumstances.

## SUMMARY

This paper is intended to introduce the reader to the terms he will be dealing with regarding metastability and it is hoped that this introduction will help him to digest the more in-depth papers that he will be reading. Philips Semiconductors uses the parameters described by Thomas Chaney of Washington University in St. Louis, Missouri because they are fundamental and the better metastability papers generally use these parameters. For further reading on the subject, the article "Metastable behavior in digital systems" by Lindsay Kleeman and Antonio Cantoni published in *IEEE Design & Test of Computers* in December of 1987, is recommended.

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### NOTES

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## Data sheet status

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Objective specification	Development	This data sheet contains the design target or goal specifications for product development. Specification may change in any manner without notice.
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