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The Effect of Tilt on Waveform State Levels and Pulse Parameters

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Abstract: *Tilt is the slope in waveform values that occurs before and/or after a waveform transition. Tilt causes a bias in the computed values of waveform state levels that may affect the value of several waveform parameters. The effects of tilt on pulse parameters are examined.*

Keywords: *distortion, pulse parameters, state levels, tilt, transition settling error, waveform*

1. INTRODUCTION

Tilt is defined by the IEEE Std-181-2003[1] as "A distortion of a waveform state wherein the overall slope over the extent of the waveform state is essentially constant and other than zero. Tilt may be of either polarity." This is shown diagrammatically in fig. 1 where several waveforms are shown with various amounts of tilt in *level*(s_1) and in *level*(s_2). (The terminology "*level*(s_2)" is the IEEE-defined method for indicating the value of state level 2.) Tilt can occur before and/or after the waveform transition. Tilt can affect waveform parameters because the values of the state levels are effected by tilt. A major source of tilt observed in waveforms is caused by ac coupling of signals.

Tilt should not be confused with transition settling error, which is defined by the IEEE Std-181-2003 as "The maximum error between the waveform value and a specified reference level within a user-specified interval of the waveform epoch. The interval starts at a user-specified instant relative to the 50 % reference level instant." Transition settling error refers to an instantaneous artifact in the waveform, whereas tilt refers to an extended artifact. Moreover, a measure of transition settling error will contain effects due to tilt.

The types of waveforms considered herein are step-like pulse waveforms (see the dark trace in fig. 1). The reason for considering only these types of waveforms is their importance in electronics technologies, such as computer, data communication, and telecommunication. Furthermore, the spectra of these types of waveforms can be computed easily using Fourier transforms with minimal pre-transform waveform processing.

The waveform acquired in a measurement process is the result of the interaction of the output of the pulse generator with a waveform recorder, such as a sampling oscilloscope.

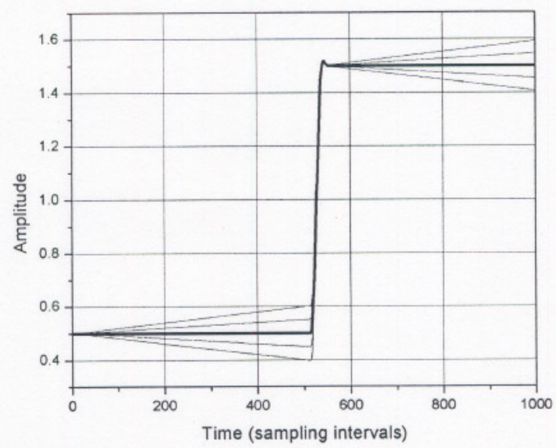

Fig. 1. Waveforms exhibiting tilt in s_1 and s_2.

Consequently, tilt can arise in a waveform because of the pulse generator and/or the sampler. Whether tilt should be considered as a bonafide characteristic of a waveform depends on the information desired. For example, if the pulse generator output is known to exhibit tilt, then its waveform and corresponding waveform parameters should exhibit tilt and its effects. In this case, case 1, tilt is part of the characteristics of the pulse generator output. On the other hand, if the pulse generator output is known not to have tilt, and tilt is observed in the waveform, then the tilt must be attributed to the characteristics of the waveform recorder; this is case 2.

For case 1 where the pulse generator is the device under test, and for case 2 where the waveform recorder is the device under test, tilt must be measured and recorded as part of the characteristics of the device under test. For case 1 where the waveform recorder is the device under test, and for case 2 where the pulse generator is the device under test, the effect of tilt must be removed from the waveform before the device under test can be accurately characterized. Removing tilt may be difficult because of the difficulty in identifying the instant tilt starts and stops and in knowing exactly the value of the state levels.

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2. OBSERVATION of TILT

Tilt can be caused by the active devices within the pulse generator (such as a step recovery diode and its bias circuitry) and sampler, or by coupling within or between the pulse generator and waveform recorder. Figure 2 shows the s_2 of a waveform that has both positive and negative tilt. This tilt is not exhibited in s_1 (see Fig. 2). For the signal shown in Fig. 2, the waveform amplitude is about 77 V. An example of how coupling can introduce tilt is shown in Fig. 3. In this case, tilt is caused by the particular waveform epoch used (see heavy solid in Fig. 3) and coupling of the timebase electronics to that of the sampler channel. The magnitude of the tilt caused by this coupling will depend on the duration of the waveform epoch.

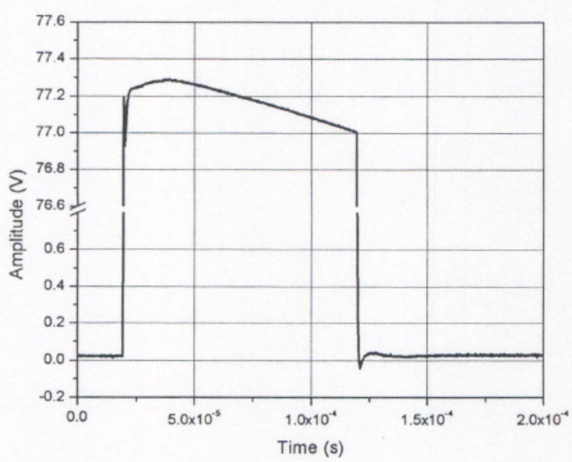

Fig. 2. Waveform with positive and negative tilt on s_2.

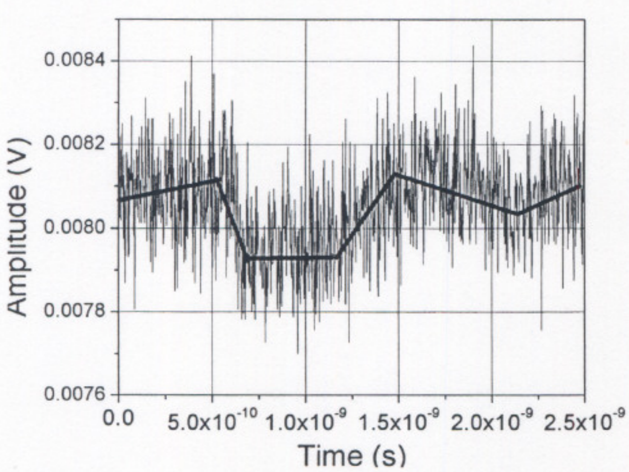

Fig. 3. Tilt caused by noise coupling from timebase and sampler electronics. The heavy line approximates the slope of the waveform.

3. EFFECT OF TILT

Although the focus here is on the effects of tilt on pulse parameters, it is worthwhile to note that tilt will also affect the spectrum of the waveform. Tilt can be modeled as a ramp function, with associated amplitude and delay, that is added to the tilt-free waveform. Consequently, the spectrum of a waveform containing tilt contains additional information related to the ramp function. If there is a tilt on either side of the transition, then two spectra are added.

In this section, the effect of tilt on waveform parameters is simulated. In this simulation, a set of M noisy waveforms are used (see Fig. 1). Noisy waveforms were used to more closely emulate measurement data. The noisy waveforms are generated by adding a noise waveform to a noise-free step-like waveform. Each noise waveform is unique but has nearly the same rms value, approximately $0.003A_p$. The noise-free step-like waveform is generated in three steps: generate an ideal 1024-element trapezoidal-like waveform where the 50 % reference level instant is located around the center of the epoch and the transition has a fixed duration, add tilt to s_1 and or s_2, and then convolve this waveform with a Butterworth filter (low pass, 2nd order). For the waveforms used here, the duration of s_1 was 512 sampling intervals, the transition was 21 sampling intervals, the duration of s_2 was 491 sampling intervals, and $A_p = 1$. The tilt added was computed using:

$$tilt = \frac{\alpha A_p}{t_1 - t_0}, \qquad (1)$$

where A_p is the waveform amplitude, α is a fraction indicating the maximum value of the tilt relative to A_p, t_1 is the last instant of tilt in s_1 or s_2, and t_0 is the first instant of tilt in s_1 or s_2. For the waveforms used herein, $t_1 - t_0$ is approximately 500 sampling intervals.

The error in the pulse parameter is computed for each waveform, yielding M values, and these M values are then averaged. These average values are what is shown in this section.

A. The effect of tilt on the state levels.

The values of the state levels, *level*(s_1) and *level*(s_2), are obtained using a histogram method[1]. The histogram is generated by filling the bins (which correspond to amplitude ranges) with the number of occurrences of waveform values that fall within a bin. Because the waveforms used here are step-like, the histogram will contain two modes, one corresponding to s_1 and one to s_2. Figure 4 shows the effect of tilt on *level*(s_1) and *level*(s_2). From Fig. 4, it can be seen that *level*(s_1) is immune to tilt in s_2. The variation in the error in

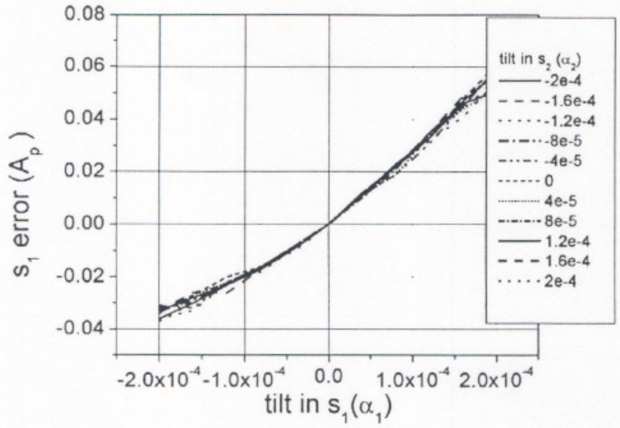

Fig. 4. Error in *level*(s_1) due to tilt in s_1 and s_2.

level(s_1) shown in Fig. 4 as a function of tilt in s_2 is an artifact of the limited number of noisy waveforms used in the simulation. By increasing the number (M) of noisy waveforms used, the variation in the value of the state levels decreases.

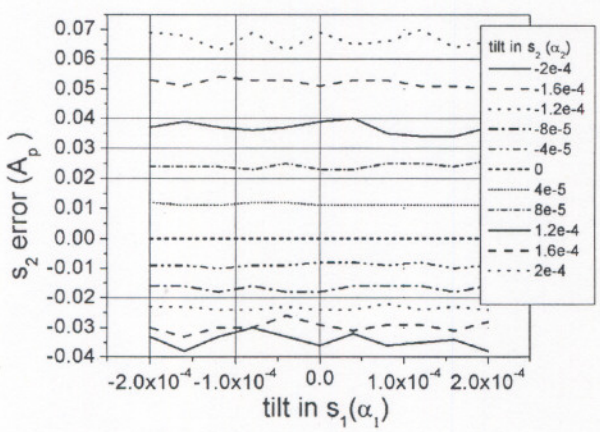

Fig. 5. Error in *level*(s_2) due to tilt in s_1 and s_2.

Figure 5 shows the effect of tilt on *level*(s_1) and *level*(s_2). From Fig. 5, it can be seen that *level*(s_2) is immune to tilt in s_1 but that it is affected by tilt in s_2. The results of Figs. 4 and 5 would be expected, that is, the value of the state level is only affected by tilt in its own state.

The values of the state levels with tilt can be approximated by:

$$level(s) = level(s)_0 + \Delta(s), \tag{2}$$

where the "0" subscript indicates tilt-free values and Δ is the change in level value due to tilt. However, this equation and the subsequent analysis simplifies the effect of tilt on level(s_1) and level(s_2), which can be seen from Figs. 4 and 5 to be nonlinear.

B. The effect of tilt on waveform amplitude

The tilt-free waveform amplitude, $A_{p,0}$, is given by:

$$A_{p,0} = level(\mathrm{s}_2)_0 - level(\mathrm{s}_1)_0. \tag{3}$$

The waveform amplitude with tilt can be approximated by:

$$A_p = level(\mathrm{s}_2) - level(\mathrm{s}_1) = level(\mathrm{s}_2)_0 + \Delta(\mathrm{s}_2) - level(\mathrm{s}_1)_0 - \Delta(\mathrm{s}_1). \tag{4}$$

Equation (4) and the following analysis make the simplifying assumption that tilt has a linear effect on *level*(s_1) and *level*(s_2). The percent error in waveform amplitude can be computed using:

$$e_A = \left(\frac{A_p - A_{p,0}}{A_{p,0}}\right)100 = \left(\frac{A_{p,0} + \Delta(s_2) - \Delta(s_1) - A_{p,0}}{A_{p,0}}\right)100 = \left(\frac{\Delta(s_2) - \Delta(s_1)}{A_{p,0}}\right)100 \tag{5}$$

Figures 6 and 7 show the effect of tilt on A_p for a pulse of a given $A_{p,0}$. As expected, tilt in either state level affects pulse amplitude. From these two figures we see that A_p is nonlinearly affected by tilt. The line labeled "ideal" in Figs. 6 and 7 is based on *level*(s_1) and *level*(s_2) being calculated using the waveform value when the tilt has reached half its value, that is at $(t_1 - t_0)/2$, which gives:

$$level(\mathrm{s}_1)_\mathrm{i} = level(\mathrm{s}_1)_0 + \frac{\alpha_1 A_p}{2} \tag{6}$$

and

$$level(\mathrm{s}_2)_\mathrm{i} = level(\mathrm{s}_2)_0 + \frac{\alpha_2 A_p}{2}, \tag{7}$$

where, for the cases examined here, $-0.1 \le \alpha_1,\alpha_2 \le 0.1$. The ideal percent amplitude error, $e_{A,\mathrm{i}}$ using (6) or (7) in (5) is:

$$e_{A,i} = \frac{\alpha}{2}100. \tag{8}$$

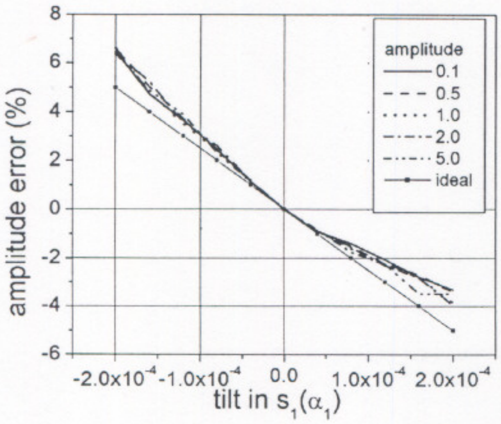

Fig. 6. Amplitude error due to tilt in s_1 and as a function of pulse amplitude.

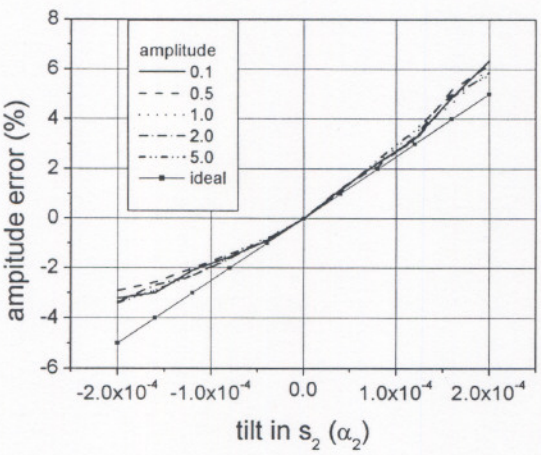

Fig. 7. Amplitude error due to tilt in s_2 and as a function of pulse amplitude.

The reason $e_{A,} \neq e_{A,i}$, see Figs. 5 and 6, is due to the histogram and how it is affected by the curvature of the waveform near the end of s_1 and beginning of s_2, as will now be discussed. The histogram effect on s_1 tilt will be discussed first.

For negative tilt in s_1, the s_1 mode count is filled by occurrences of values from both the tilt and transition regions of the waveform. As the tilt becomes more negative, the contribution to the s_1 mode bin count from the tilt region decreases. Consequently, to increase the s_1 mode bin count with increasing s_1 negative tilt, the s_1 mode bin moves closer to the inflection point where the waveform changes from s_1 to the transition (around 500 sampling intervals in Fig. 1). For positive tilt in s_1, the s_1 mode count is filled primarily by occurrences of values from the tilt region and some from the inflection region of the waveform. As the tilt becomes more positive, the contribution to the s_1 mode bin count from the inflection region decreases and the s_1 mode bins moves away from the inflection point.

A similar process occurs for tilt in s_2. As the s_2 tilt becomes more negative, the s_2-associated mode of the histogram again shifts closer to where the waveform changes from s_2 to the transition (around 550 sampling intervals in Fig. 1), near the second important inflection point. Positive tilt in s_2 causes the s_2 mode bin to move away from the second inflection point thereby increasing A_p.

The effect of noise and tilt in s_2 on pulse amplitude was also examined; the results are shown in Fig. 8. The effect of noise on pulse amplitude, in the presence of tilt in s_2, is observable but small compared to the effect of tilt. As the noise increases from $0.001A_p$ rms to 0.05 A_p rms, the noise linearity between pulse amplitude and amplitude error appears to improve. For noise greater than about 0.05, the correlation between amplitude error and tile decreases with increasing noise.

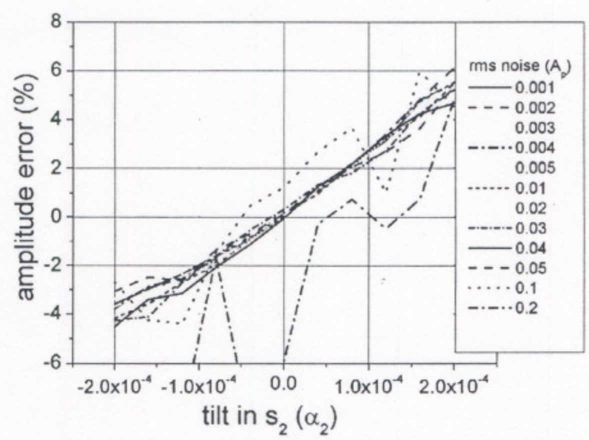

Fig. 8. The effect of noise and tilt on pulse amplitude error.

C. The effect of tilt on pulse transition duration

The values of the transition duration, t_d, are defined as the difference between the instants that the waveform crosses two reference levels, which for the work done here are the 10 % and 90 % reference levels. The t_d is thus calculated using[1]:

$$t_d = t_{90\%} - t_{10\%}, \tag{9}$$

where $t_{90\%}$ and $t_{10\%}$ are the instants the waveform crosses the 90 % and 10 % reference levels. The error in the transition duration, e_t, is given by:

$$e_t = \frac{t_d - t_{d,0}}{t_{d,0}} 100, \tag{10}$$

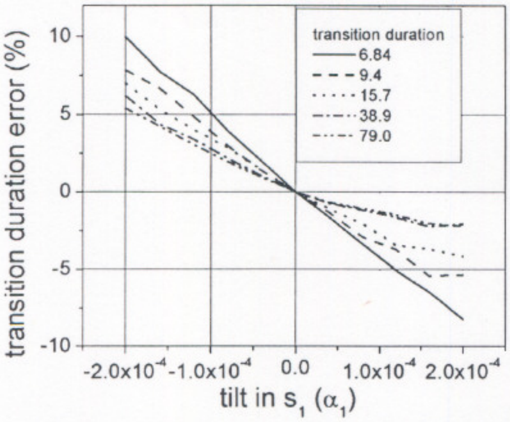

Fig. 9. Transition duration error as a function of tilt in s_1 for waveforms having different transition durations.

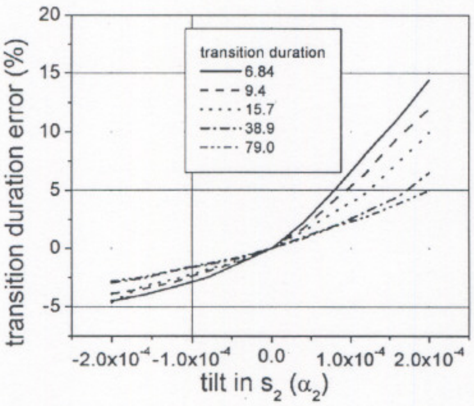

Fig. 10. Transition duration error as a function of tilt in s_2 for waveforms having different transition durations.

where $t_{d,0}$ is the 10 % to 90 % transition duration of the tilt-free waveform. The transition duration errors are shown in Figs. 9 and 10. The transition duration shown in the key of these figures is in arbitrary time units (sampling intervals). The results shown in Figs. 9 and 10 are expected: negative tilt in s_1 or positive tilt in s_2 increases the pulse amplitude and this will increase the duration between the two reference level instants. Positive tilt in s_1 or negative tilt in s_2, on the other hand, reduce the pulse amplitude and this decreases the duration between the two reference level instants.

D. The effect of tilt on pulse parameter uncertainty

As can be seen from the previous sections, tilt introduces a bias onto *level*(s_1) and *level*(s_2), which in turn biases the values of pulse amplitude and transition duration. The ideal situation would be to remove the tilt in the waveform, if appropriate (that is, for case 1, as mentioned in Section 1). If the device being measured exhibits tilt (case 2), the effect of tilt will be to increase the variation of the *level*(s_1) and/or *level*(s_2), and this will increase the variation of pulse amplitude and transition duration (see analysis in ref. 2). In case 1 tilt may be difficult to remove or reduce because it may be difficult to locate the instant that the tilt started or stopped. Therefore, as for the situation for case 2, the effects of tilt must be added, via proper uncertainty propagation methods, to the uncertainty of the pulse parameter. The tilt-based bias can be added symmetrically or asymmetrically to the pulse parameter uncertainty. The more conservative approach would be to use the largest bias and add this symmetrically to the parameter uncertainty.

REFERENCES

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