Calibration of pulse generators – measurement uncertainty evaluation

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Contents

• **Introduction**
  • Measurement of one spectrum line amplitude
  • Fourier transform of time-domain pulse waveform
  • Intermediate-frequency measurement method
  • Calibration of other parameters
  • Conclusion
• general measurement uncertainty formulas apply
• expanded uncertainty of the measurement \( U_M = k \cdot u_M \)  
  \( (u_M = \) standard measurement uncertainty, \( k = \) coverage factor)  
• standard measurement uncertainty (A and B components)

\[
u_M = \sqrt{u_{MA}^2 + u_{MB}^2}
\]

• type-A measurement uncertainty

\[
u_{MA} = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \bar{x})^2}{N \cdot (N - 1)}}
\]

\[
\bar{x} = \frac{1}{N} \cdot \sum_{i=1}^{N} x_i
\]

• type-B measurement uncertainty \( u_{BM} = \sqrt{\sum_{i=1}^{N} u_{BMi}^2} \)
Introduction

• full traceability – some of measurements challenging
  – digital real-time oscilloscope traceability
  – digital sampling-oscilloscope traceability

• only measurement uncertainty of most used methods will be discussed
• Introduction
• **Measurement of one spectrum line amplitude**
• Fourier transform of time-domain pulse waveform
• Intermediate-frequency measurement method
• Calibration of other parameters
• Conclusion
Measurement of one spectrum line amplitude

- measurement setup

![Diagram of measurement setup]

- main uncertainty contributions

<table>
<thead>
<tr>
<th>source</th>
<th>uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>measuring receiver</td>
<td>resolution uncertainty</td>
</tr>
<tr>
<td></td>
<td>other components</td>
</tr>
<tr>
<td>power sensor</td>
<td>harmonic signal level</td>
</tr>
<tr>
<td>measuring receiver?</td>
<td>other uncertainties of the method</td>
</tr>
<tr>
<td>pulse generator?</td>
<td></td>
</tr>
<tr>
<td>impedance mismatch</td>
<td>pulse generator &lt;-&gt; measuring receiver</td>
</tr>
<tr>
<td></td>
<td>power splitter &lt;-&gt; measuring receiver</td>
</tr>
<tr>
<td></td>
<td>power splitter &lt;-&gt; power sensor</td>
</tr>
</tbody>
</table>

Workshop on characterization of pulse generators, 24. 5. 2017, INTA
Measurement of one spectrum line amplitude

- resolution uncertainty

\[ u_{BM1} = \frac{LSD}{2\sqrt{3}} \]

LSD = least significant digit

- other uncertainties of the receiver
  - time stability
  - repeatability of the reading

- level of harmonic signal
  - specifications or calibration certificate of the power sensor

- impedance mismatch

\[ u_M = \frac{1}{\sqrt{2}} 20 \log(1 + |\Gamma_1||\Gamma_2|) \]
• Introduction
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Fourier transform of time-domain pulse waveform

- direct acquisition of the pulse generator output using an oscilloscope and conversion to the frequency domain

\[ S(f) = 2|V(f)| \]

- method useful for base band pulse generators
- simple, time efficient
- oscilloscope, attenuator and cables may influence the pulse properties – **correction** must be taken into account
Fourier transform of time-domain pulse waveform

- oscilloscope
  - digital real-time oscilloscope (DRTO): triggers directly using the measured pulse

- digital sampling oscilloscope (DSO): equivalent-time sampling, needs an external trigger signal
Fourier transform of time-domain pulse waveform

- main uncertainty contributions

<table>
<thead>
<tr>
<th>source</th>
<th>uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>oscilloscope</td>
<td>correction of the frequency response</td>
</tr>
<tr>
<td></td>
<td>waveform acquisition</td>
</tr>
<tr>
<td>attenuator(s)</td>
<td>attenuation uncertainty</td>
</tr>
<tr>
<td>impedance mismatch</td>
<td>pulse generator &lt;-&gt; attenuator</td>
</tr>
<tr>
<td></td>
<td>attenuator &lt;-&gt; oscilloscope</td>
</tr>
<tr>
<td></td>
<td>(delay line &lt;-&gt; oscilloscope)</td>
</tr>
<tr>
<td>signal processing</td>
<td>interpolation of FFT</td>
</tr>
</tbody>
</table>
Fourier transform of time-domain pulse waveform

- correction of the oscilloscope frequency response
  - exact calculation rather complicated (uncertainty propagation between time and frequency domain, correlations)
  - uncertainty of the deconvolution and regularization
  - an overestimated guess is a safe option (ripple of the amplitude and phase response, numerical simulation)


Fourier transform of time-domain pulse waveform

- uncertainty of the waveform acquisition
  - time-base uncertainty
    \[ u_r = \frac{1}{\sqrt{6}} \frac{n_{total}}{n_{used}} 2^{-N} \cdot 100 \quad (\%; \text{div}; \text{div}) \]
  - vertical resolution (from effective number of bits)
    \[ u_r = \frac{1}{\sqrt{6}} \frac{n_{total}}{n_{used}} 2^{-N} \cdot 100 \quad (\%; \text{div}; \text{div}) \]

\( N \) is the effective number of bits
\( n \) is the number of vertical divisions
triangular distribution
Fourier transform of time-domain pulse waveform

- attenuation uncertainty
  - VNA measurement
  - repeatability, VNA uncertainties or manufacturer specification
  - combination of a cable, power splitter and attenuator parameters
Fourier transform of time-domain pulse waveform

- impedance mismatch (DSO example)
  - attenuator <-> oscilloscope
  - attenuator <-> power splitter
  - power splitter <-> delay line
  - delay line <-> oscilloscope
Fourier transform of time-domain pulse waveform

- signal processing
  - deconvolution, regularization
  - FFT uncertainties

➔ difficult to take into account, based on experience and deep understanding of the DSP algorithms
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Intermediate-frequency measurement method

- measurement setup
### Intermediate-frequency measurement method

- **main uncertainty contributions**

<table>
<thead>
<tr>
<th>uncertainty source</th>
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<tbody>
<tr>
<td>oscilloscope</td>
<td>horizontal unc.</td>
</tr>
<tr>
<td></td>
<td>vertical unc.</td>
</tr>
<tr>
<td>measuring receiver</td>
<td>transfer function, resolution</td>
</tr>
<tr>
<td></td>
<td>impulse bandwidth (IBW) determination</td>
</tr>
<tr>
<td></td>
<td>other uncertainties</td>
</tr>
<tr>
<td>power sensor / selective level meter</td>
<td>uncertainty of the level of harmonic signal</td>
</tr>
<tr>
<td>impedance mismatch</td>
<td>mismatch between the generator and meas. receiver</td>
</tr>
<tr>
<td></td>
<td>mismatch between the CW generator and meas. receiver</td>
</tr>
<tr>
<td></td>
<td>mismatch between the CW generator and the power sensor</td>
</tr>
</tbody>
</table>
Intermediate-frequency measurement method

oscilloscope uncertainties

- only digital-real time oscilloscope unc. discussed (we are integrating an area under the envelope curve, difficult with analogue oscilloscope)
- vertical resolution

\[ u_r = \frac{1}{\sqrt{6}} \frac{n_{total}}{n_{used}} 2^{-N} \cdot 100 \quad (\% ; \text{div} ; \text{div}) \]

\( N \) is the effective number of bits
\( n \) is the number of vertical divisions
triangular distribution
Intermediate-frequency measurement method

Oscilloscope uncertainties

- horizontal resolution (time base accuracy)

\[ u_{osc} = \frac{1}{\sqrt{6}} \frac{n_{total}}{n_{used}} \frac{1}{N_h} \cdot 100 \text{ (\%; div; div)} \]

\[ N_h = \text{overall number of horizontal points at osc. screen} \]

\[ n = \text{number of horizontal divisions} \]

triangular distribution

- trigger jitter – DSO needs 1000 trigger events for 1000 sampling points
Intermediate-frequency measurement method

oscilloscope uncertainties

- transfer function
  - not important, as we measure a low-bandwidth signal without sharp edges, the shape of the measured signal; is not significantly influenced by the oscilloscope

- DC gain – calibrated using a voltmeter & DC source

- noise contribution for small CISPR signal levels

- input reflection coefficient
  - scalar/vector network analyzer or manufacturer specifications (rectangular probability distribution)

\[
 u_M = \frac{1}{\sqrt{2}} 20 \log(1 + |\Gamma_1||\Gamma_2|)
\]
Intermediate-frequency measurement method

measuring receiver uncertainties

- impulse bandwidth
  - not easily measurable, see the presentation *Calibration of measurement receivers with quasi-peak detector*
  - typically measured using both methods recommended in CISPR 16-1-1 and the difference between results is taken as the measurement uncertainty
  - typ. 0.15 dB, rectangular distribution

- input reflection coefficient
  - scalar/vector network analyzer or manufacturer specifications (rect. distribution)
  \[
  u_M = \frac{1}{\sqrt{2}} 20 \log(1 + |\Gamma_1||\Gamma_2|)
  \]
Intermediate-frequency measurement method

measuring receiver uncertainties

• level measurement
  – uncertainty of measurement at high level – comparison with a calibrated power sensor or manufacturer specifications
  – receiver linearity – using a calibrated step-attenuator or manufacturer specifications
  – rectangular probability distribution
Intermediate-frequency measurement method

power sensor uncertainties

- calibration factor
- impedance mismatch
- linearity
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Calibration of other parameters

- generator output reflection coefficient
  - difficult to measure, as the ON/OFF states have very different voltage reflection coefficients

- pulse repetition rate
  - frequency counter + uncertainties
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Conclusion

- limits of uncertainty in CISPR 16-1-1 / EN 55016-1-1 rather large
- different methods may lead to different uncertainties
- selection of the method dependent on the frequency and equipment available (oscilloscope, power sensor, measuring receiver)
EMPIR project “15RPT01 Development of RF and microwave metrology capability”
http://rfmw.cmi.cz/

Thank you for attention