NON-LINEAR SUPERPOSITION OF BROADBAND SPECTRA FOR FAST EMISSION MEASUREMENTS IN TIME DOMAIN

C. Keller, K. Feser
Institute of Power Transmission and High Voltage Technology,
University of Stuttgart, Germany
(Principal contact: ckeller@ieh.uni-stuttgart.de)

Abstract: According to the standards, emission measurements are carried out in the frequency domain using a test receiver. In this paper the set-up and procedures of a measuring system in the time domain is presented. The advantage of this system is, that measurements can be done approximately 10 to 100 times faster. A special procedure to measure a pulse was already described in [2]. This paper presents a procedure to calculate the spectrum of the *superposition of two pulses*. The difficulty hereby is the non-linearity of the detectors.

1. Introduction

Emission measurements for the EMC check of a device must be carried out (according to the standard [4]) in the frequency domain with e.g. a test receiver. It is necessary to execute a frequency sweep and to measure the emission at each frequency. This method has the disadvantage that the measurement lasts, depending on the selection of the parameters, for a quite a long time (typically 10 to 30 min). Since a long measurement always implies high costs, it is profitable to look up for possibilities to shorten the measurements without a loss of quality.

In particular, the measurement in the time domain provides a good possibility to save time. Instead of measuring in the frequency domain with a test receiver, several single shots are recorded with an oscilloscope. From these data a comparable spectrum can be calculated by using the discrete Fourier transform (DFT) and several correction procedures. In this paper the time domain measuring system FEMIT (Fast Emission Measurement In Time Domain) is described.

1.1 Measurement set-up

When measuring in the frequency domain, the signal is recorded directly with the test receiver, which executes a frequency sweep. This measuring set-up in comparison to FEMIT is shown in Figure 1.

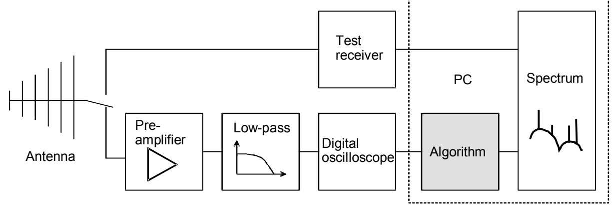

Fig. 1: Measurement set-up

The central device for FEMIT is a digital oscilloscope. If the noise level has to be lower than approximately 10 dB below the limits (EN 55011, etc.), it is necessary to use a preamplifier. To make sure, that the sampling theorem is kept, an appropriate anti-aliasing low-pass should be connected in series to the oscilloscope.

1.2 Basic procedure of evaluation

The basic FEMIT procedure consists of a DFT, a smoothing procedure and a correction. The correction takes all frequency characteristics (antenna factor, low-pass, etc.) into account, so that narrow-band signals are measured correctly. This basic procedure was already described in detail [1], [3].

1.3 Procedure for one pulse

Pulses with a repetition frequency less than the bandwidth of the test receiver, have to be measured by a special procedure. The procedure was explained in detail in [2] and is described here shortly by the example in Fig. 2.

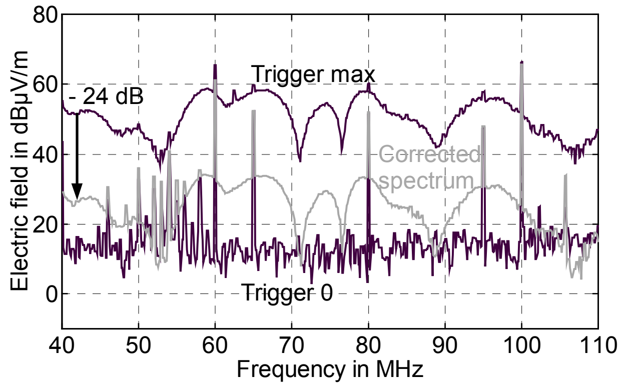

Fig. 2: Measurement procedure for pulses by an example

First, the trigger of the oscilloscope is set to a relatively high level in order to record a pulse. The spectrum is calculated by applying the basic procedure (curve "Trigger max") and is corrected for all frequencies according to the correction value given by the correction curve (Fig. 3) at the repetition frequency f_{rep} of the pulse.

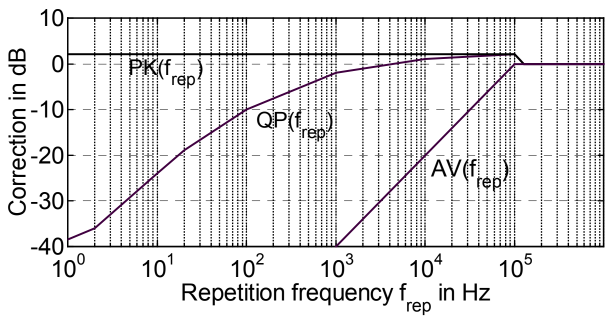

Fig. 3: Correction curves for peak PK(f_{rep}), quasi-peak QP(f_{rep}) and average detector AV(f_{rep}). Capture time 10 µs, 120 kHz band-pass

Formula (1) describes this correction by the example of the quasi-peak detector as

$$u' = u + \mathrm{QP}\left(f_{\mathrm{rep}}\right). \qquad (1)$$

Here, u is the level (at any measurement frequency) after the DFT, u' is the level after the correction. QP(f_{rep}) represents the correction value according the correction function (Fig. 3). In the example the curve "Trigger max" is shifted down 24 dB (f_{rep} = 10 Hz).
For the correct measurement of narrow-band peaks, a second measurement has to be recorded without a pulse (trigger level 0), because narrow-band peaks below the level of the (uncorrected) broadband spectrum cannot be located. The corresponding spectrum "Trigger 0" in Fig. 2 contains all the narrow-band peaks with the correct level.
In a last step the two spectra are combined: the broadband parts are taken from the first, attenuated measurement, the narrow-band parts (peaks) from the second measurement.

1.4 Time consumption and accuracy

The time consumption of one FEMIT measurement is, depending on the parameters, 10 - 100 times lower than the one of a test receiver measurement; one measurement takes ≈ 5 - 15 s. The error is typically < 1 dB for narrow-band signals and < 1 - 3 dB for broadband signals.

1.5 Typical applications

Typical applications for FEMIT are quick previews, repeated emission checks and the measurement of short or rare phenomena (e.g. switching impulse, flashover). The height scan and the check of the direction of highest emission can be performed fast. Furthermore, the emission of different modes of operation of a device can be measured separately.

2. Superposition of several pulses

The so far described procedure calculates the correct spectrum when the signal contains (apart from the narrow-band signals) *one pulse with the repetition frequency* f_{rep}. Often, several pulses with different repetition frequencies are present in the signal. Even a single rectangular signal has to be interpreted as the superposition of two pulses with the same repetition frequency, because the rising and falling edges often show different shapes and therefore different spectra. This paper presents a procedure to measure and calculate the spectra of *two pulses.*

2.1 Procedure for 2 pulses

Fig. 5 shows the principal procedure for the measurement of two pulses. The base of the procedure are three records of the oscilloscope: a record of pulse 1, a record of pulse 2 and a record without a pulse (Fig. 4).
As the period of the pulses is much longer than the capture time T of the oscilloscope (T = 10 µs, settings according to [2]), it is easy to separate the three parts by using different trigger conditions.

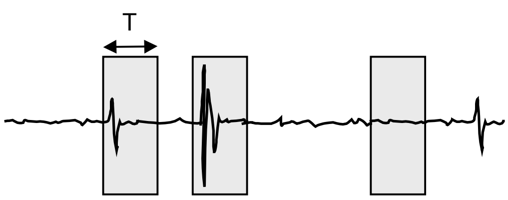

Fig. 4: Record of pulse 1, record of pulse 2 and a record without a pulse (narrow-band part of the spectrum)

After the discrete Fourier transform the spectra of the two pulses are corrected separately according to the correction curve (Fig. 3) of the simulated detector. This correction is carried out in the same way as if only the regarded pulse was present like in chapter 1.3.
Now, at each frequency the level of the superposition level u_s is calculated as a function of the detector, the repetition frequencies ($f_{\mathrm{rep1}}, f_{\mathrm{rep2}}$) and the levels of two separately attenuated spectra (u'_1, u'_2). The calculation of this function is the main subject of this paper.

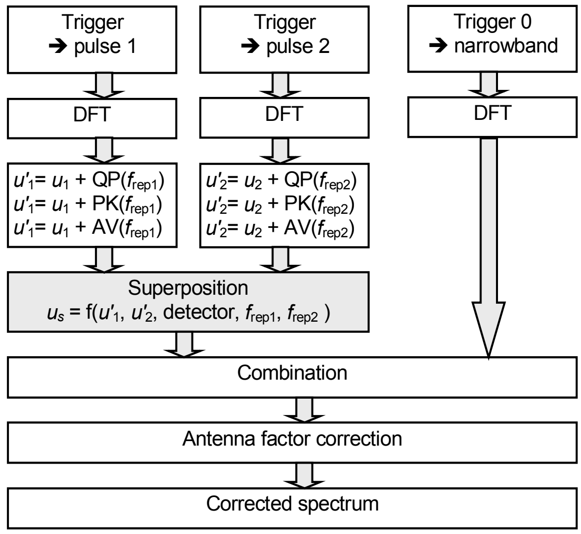

Fig. 5: Principal procedure for the measurement of two pulses

2.2 Average detector

The mentioned function depends on the detector of the test receiver that has to be simulated. The average detector shows linear behaviour: the correction curve AV(f_{rep}) for the average detector rises with 20 dB/decade for all repetition frequencies. According to the superposition principle in a linear system, the output of the sum of two input signals equals the sum of the output of the single outputs. This can be described with the response $u_2 = \mathrm{w}\{u_1\}$as a function of the input signal u_1 as

$$\mathrm{w}\{a_1\, u_{11} + a_2\, u_{12}\} = a_1 \mathrm{w}\{\, u_{11}\,\} + a_2 \mathrm{w}\{\, u_{12}\,\}. \qquad (2)$$

Therefore, the resulting spectrum can be calculated by simply adding the two spectra at each frequency. The superposition function in the gray box (Fig. 5) can be described by

$$u_S = u'_1 + u'_2 \ . \qquad (3)$$

Of course, this has to be done with the magnitudes and not with the "dB-values". The result in the dB-scale is in the range between the higher of the two levels and 6 dB above it (= double value for equal levels). However, as the average detector attenuates pulses very strongly (Fig. 3), this detector is usually used for precise measurements of narrow-band signals with low noise level and not for pulse measurements.

2.3 Peak detector

The peak detector has an extreme non-linear behaviour. It keeps the maximum value in the regarded time at each frequency (see Fig. 6).Therefore, the level of the higher of the separately corrected level equals the result of the test receiver:

$$u_S = \max\left(u'_1\, , u'_2\right) \ . \qquad (4)$$

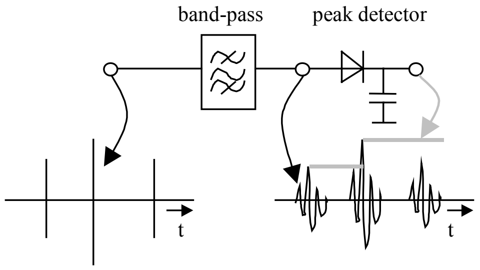

Fig. 6: Peak detector of the test receiver in the time domain

Fig. 7 shows an example for the measurement of two pulses. The two curves represent the separately corrected spectra.

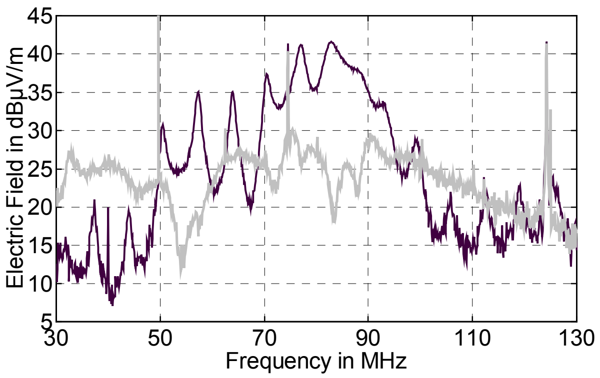

Fig. 7: Example for peak detector measurement: separately corrected spectra of two pulses ...

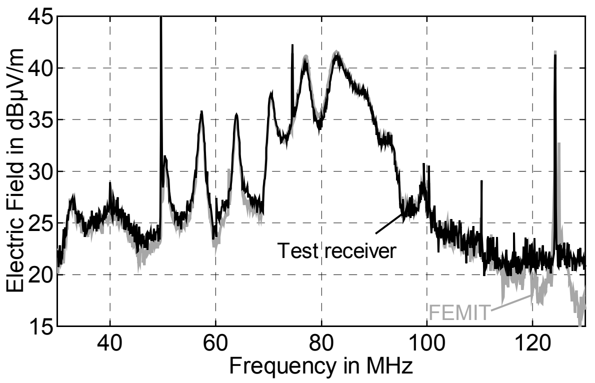

Fig. 8: ... and the FEMIT and test receiver results

In the next figure (Fig. 8) the result of FEMIT and the test receiver measurement is shown for this example. It is obvious that the agreement is rather good. Differences for f > 120 MHz are due to the fact that the noise level of FEMIT is lower.

2.4 Quasi-peak detector

In contrast to the average and peak detector, the quasi-peak detector is much more complicated to describe because of its non-linearity. The following example illustrates this:

Let's consider two equal pulses of $f_{rep1} = f_{rep2}$ = 1 kHz. In a linear system, the spectrum of the superposition would be 6 dB = × 2 higher (compared to a single spectrum) for all frequencies. As the quasi-peak detector interpretes this signal as one pulse with 2 kHz, the spectrum of this signal is (according to the pulse response characteristic in Fig. 3) just 1 dB higher as the spectrum of a 1 kHz pulse. The difference between linear superposition and the quasi-peak result is 5 dB in this example.

Due to the non-linearity, it is not possible to calculate the mentioned function analytically. Therefore, the next chapters describe a procedure that approximates rather well the behaviour of the quasi-peak detector.

3. Calculation of the non-linear superposition of the quasi-peak detector

3.1 Principle I: Combining 2 pulses of equal amplitude

In test receiver measurements, the measured level of a pulse depends mainly on the amplitude and repetition frequency of the signal between the output of the band-pass and the detector. Now, the principal idea for the procedure is that *two pulses* with the *same amplitudes* u_1, u_2 (after the band-pass) and the repetition frequencies f_{rep1} and f_{rep2} can virtually be combined to *one pulse* with the *repetition frequency* $f_{rep1} + f_{rep2}$.

Simulations of the detector show that the measurement does not depend on the distribution of the pulses: a pulse with a regular repetition frequency and a mixture of (equal) pulses with the same number of pulses/s shows the same result.

3.2 Principle II: Adjusting different levels

In general, two pulses with different levels have to be considered. To apply the described idea, the levels have to be adjusted. Therefore, the level of one of the pulses is adjusted to the other (Fig. 9a: gray pulse + x dB). To compensate the error of the changing of the level, the repetition frequency of this pulse is altered according to the pulse response curve of the detector (Fig. 9b: $f_{rep2} \rightarrow f_{rep2}'$).

For example: The attenuation of a 100 Hz pulse is 8 dB lower than the attenuation of a 1000 Hz pulse. Therefore, a pulse with 1000 Hz and a level of y dB shows the same level as a 100 Hz pulse with y + 8 dB.

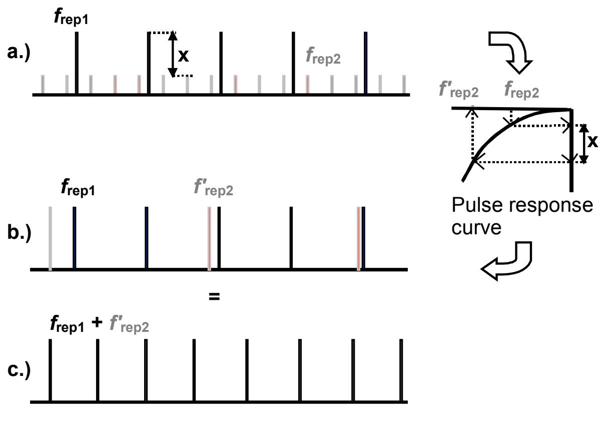

Fig. 9: Adjustment of the pulses

After this adjustment, the pulses have equal amplitudes (at the regarded frequency) and therefore the result can be regarded as one pulse with the repetition frequency $f_{reps} = f_{rep1} + f'_{rep2}$ (Fig. 9c). So, the idea is to replace the two pulses of different amplitudes and repetition frequencies by *one* pulse of *one* amplitude and *one* repetition frequency.

3.3 Adjusting of the level

Fig. 10 shows the further on used definitions of the levels. u_1 and u_2 are the levels in the spectrum (at a frequency f_0) of pulse 1 and 2 after applying the DFT. The attenuation of the quasi-peak detector for a pulse with repetition frequency f_{rep1}, f_{rep2} is given as QP(f_{rep1}), QP(f_{rep2}) as shown in Fig. 3 (negative values in dB). The separately attenuated levels are defined as u'_1 respectively u'_2:

$$u'_i = u_i + \mathrm{QP}\left(f_{\mathrm{rep}i}\right), \quad i = 1,2 \,. \tag{5}$$

The difference between these levels is Δ'. The increase (depending on the reference level) of the superposition in relation to the higher of the two attenuated levels (u'_1 in Fig. 10) is defined as Δ_{s1}, Δ_{s2} and Δ_s.

As the level of the superposition always has to be located between the higher of the attenuated levels and 6 dB above that, it makes sense to define the function for the calculation of the superposition as the increase Δ_s as a function of Δ' and the repetition frequencies: $\Delta_s = \mathrm{f}\,(\Delta', f_{\mathrm{rep1}}, f_{\mathrm{rep2}})$.

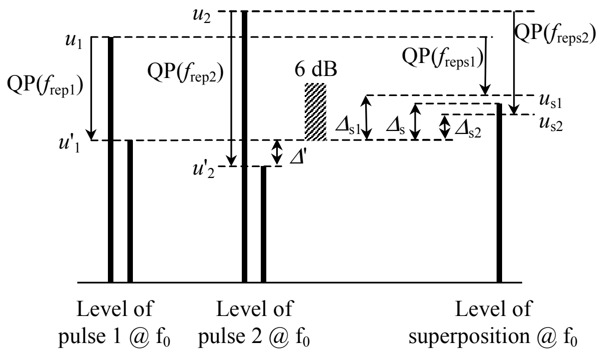

Fig. 10: Definition of the levels

For the following formulas the inverse function of QP(f_{rep1}) is necessary. Therefore, the inverse function is defined as $\mathrm{QP}^{-1}(f_{\mathrm{rep}})$:

$$\mathrm{QP}^{-1}\left(\mathrm{QP}\left(f_{\mathrm{rep}}\right)\right) = f_{\mathrm{rep}} \tag{6}$$

As the results depend on the fact, whether pulse 2 is adjusted to pulse 1 or vice versa, these two cases are regarded separately:

- Adjusting level of pulse 2 to pulse 1:

To adjust u_2 to u_1, the repetition frequency of pulse 2 has to be changed to f'_{rep2}:

$$f'_{\mathrm{rep2}} = \mathrm{QP}^{-1}\left(\mathrm{QP}\left(f_{\mathrm{rep2}}\right) + u_2 - u_1\right) \,. \tag{7}$$

Now, the pulses can be regarded as one pulse with the repetition frequency f_{rep1} and the level u_{s1} after the detector

$$f_{\mathrm{reps1}} = f_{\mathrm{rep1}} + f'_{\mathrm{rep2}} \tag{8}$$

$$u_{s1} = u_1 + \mathrm{QP}\left(f_{\mathrm{reps1}}\right) \,. \tag{9}$$

Combining (9), (7) and (5) the level of the superposition is given as

$$\begin{aligned} u_{s1} = {} & u'_1 - \mathrm{QP}\left(f_{\mathrm{rep1}}\right) \\ & + \mathrm{QP}\left(f_{\mathrm{rep1}} + \mathrm{QP}^{-1}\left(\mathrm{QP}\left(f_{\mathrm{rep1}}\right) + u'_2 - u'_1\right)\right) \end{aligned} \tag{10}$$

- Adjusting level of pulse 1 to pulse 2:

The level of the superposition for adjusting pulse 1 to pulse 2 can be obtained in the same way:

$$\begin{aligned} u_{s2} = {} & u'_2 - \mathrm{QP}\left(f_{\mathrm{rep2}}\right) \\ & + \mathrm{QP}\left(f_{\mathrm{rep2}} + \mathrm{QP}^{-1}\left(\mathrm{QP}\left(f_{\mathrm{rep2}}\right) + u'_1 - u'_2\right)\right) \end{aligned} \tag{11}$$

3.4 From absolute levels to differences

To get a relation for the increase of the higher of the attenuated levels as a function of the difference Δ' between the attenuated levels, u'_1 is now defined as a reference level and shall be the higher level:

$$u'_1 = 0\,\mathrm{dB}, \quad u'_1 \geq u'_2 \,. \tag{12}$$

Δ' according to Fig. 10 is therefore given as

$$\Delta' = u'_1 - u'_2 = -\,u'_2 \tag{13}$$

and the increase of the superposition in relation to the higher of the attenuated levels as Δ_{s1} (level of pulse 2 adjusted to pulse 1) respectively Δ_{s2} (vice versa)

$$\begin{aligned} \Delta_{s1} &= u_{s1} - u'_1 = u_{s1} \,, \\ \Delta_{s2} &= u_{s2} - u'_1 = u_{s2} \,. \end{aligned} \tag{14}$$

Using (12), (13) and (14), (10) and (11) become

$$\begin{aligned} \Delta_{s1} = {} & -\,\mathrm{QP}\left(f_{\mathrm{rep1}}\right) \\ & + \mathrm{QP}\left(f_{\mathrm{rep1}} + \mathrm{QP}^{-1}\left(\mathrm{QP}\left(f_{\mathrm{rep1}}\right) - \Delta'\right)\right) \end{aligned} \tag{15}$$

$$\begin{aligned} \Delta_{s2} = {} & -\,\Delta' - \mathrm{QP}\left(f_{\mathrm{rep2}}\right) \\ & + \mathrm{QP}\left(f_{\mathrm{rep2}} + \mathrm{QP}^{-1}\left(\mathrm{QP}\left(f_{\mathrm{rep2}}\right) + \Delta'\right)\right) \end{aligned} \tag{16}$$

3.5 Average of Δ_{s1} and Δ_{s2}

According to (12), Δ_{s1} (Δ_{s2}) is the increase for the case that the lower (higher) attenuated level is adjusted to the higher (lower) attenuated level. An investigation of (15) and (16) shows that the results for the increase are different, if the repetition frequencies are not equal (Fig. 11).

To find the best result, measurements were made. The comparison shows that the *average* Δ_s (in the dB-scale) of Δ_{s1} and Δ_{s2} fits rather good to the measurements (see 3.7 "Comparison to measurements"). Therefore, always the average of Δ_{s1} and Δ_{s2} is used for the calculation of the superposition Δ_s :

$$\Delta_s = \frac{\Delta_{s1} + \Delta_{s2}}{2} \,. \tag{17}$$

Fig. 11 shows for a pair of repetition frequencies the curves for Δ_{s1}, Δ_{s2} and the corresponding measurement. The upper curve represents the correction that would be used for linear addition.

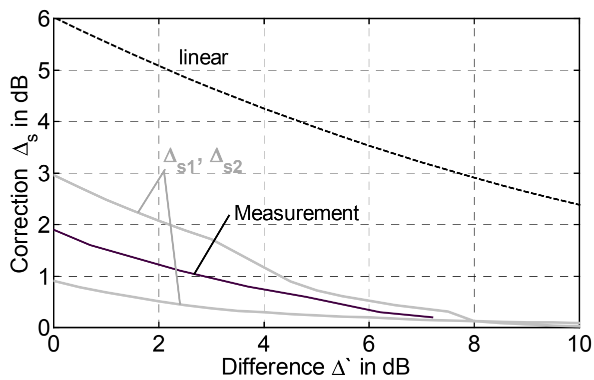

Fig. 11: Δ_{s1}, Δ_{s2} , measurement and linear superposition for one example ($f_{\mathrm{rep1}} = 1000$ Hz, $f_{\mathrm{rep2}} = 100$ Hz)

3.6 Higher and lower repetition frequency

Investigations of Δ_s show that for a given pair of two repetition frequencies Δ_s depends on the fact, whether the higher attenuated level belongs to the lower repetition frequency or vice versa.

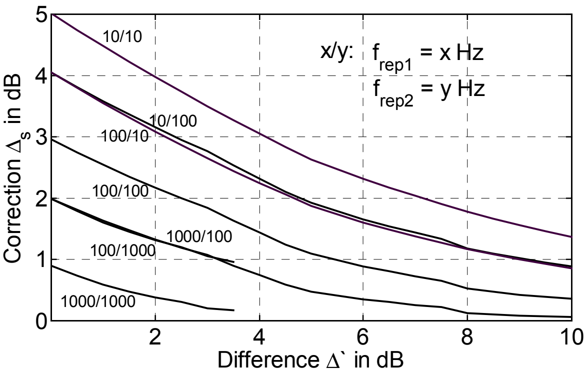

Fig. 12: Average Δ_s of Δ_{s1} and Δ_{s2} for several pairs of repetition frequencies

Fig. 12 shows Δ_s for several pairs of repetition frequencies. The notation in the figure "x/y" means, that for this curve the pulse with f_{rep} = x Hz had the higher attenuated level compared to the other pulse with f_{rep} = y Hz.

The parameter of the abscissa Δ' is the difference between the attenuated single levels and the parameter of the ordinate is the increase of the superposition in relation to the higher attenuated level.

A comparison shows that the difference is very small (≈ 0.1 – 0.2 dB). Therefore, it is not necessary to distinguish these two cases. This means that the principal four possible results for a pair of pulses reduce to *one resulting curve*. Here, only the difference Δ' of the attenuated levels is the parameter for the increase.

3.7 Comparison to measurements

As already mentioned, measurements with the test receiver were made to verify these results that are based on assumptions.

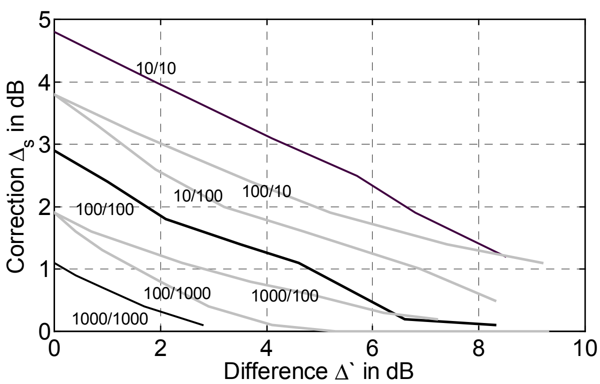

Fig. 13: Measurement of Δ_s for some pairs

Combinations of measured pairs of repetition frequencies (f_{rep1}/f_{rep2}) are: 10/10, 100/100, 1000/1000, 10/100, 100/10, 100/1000, 1000/100, 10/1000, 1000/10. Fig. 13 shows the measurements for several different combinations of repetition frequencies.

The next figure (Fig. 14) shows the differences between Fig. 12 and Fig. 13, that correspond to the error of the calculation.

For most curves, the error is lower than 0.5 dB. This result is quite good compared to the general accuracy of EMC-measurement of pulses: In CISPR 16-1 the tolerance for the quasi-peak detector is given as ± 1 dB, for repetition frequencies < 20 Hz even greater!

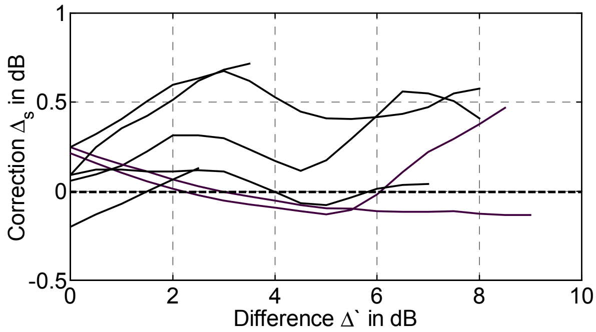

Fig. 14: Error: calculated – measured Δ_s for some measurements

3.8 Fit with exponential function

For the implementation in the measurement procedure, it is disadvantageous to calculate for each frequency of the spectrum the average Δ_s of Δ_{s1} and Δ_{s2} (formulas (17), (15) and (16)). Simulations show that the average Δ_s can be fitted rather good by a simple exponential function

$$\Delta_s = a \cdot e^{-\frac{\Delta'}{b}} \tag{18}$$

Fig. 15 shows the comparison of some calculated curves and fitted exponential curves. The error is usually less than 0.1-0.2 dB. Of course, it is possible to find a more exact fitting function, but compared to the simplicity of (18) and the discussed accuracy, this is sufficient.

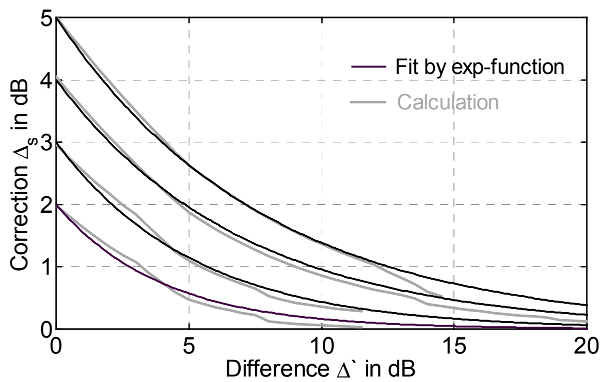

Fig. 15: Fit of some calculated averages by expon. function

As the fitting function consists of two parameters, the average of (15) and (16) has to be evaluated for two Δ', e.g. Δ' = 0 and Δ' = 4. From these two equations, the parameters *a* and *b* can be determined as

$$a = \Delta_s(0),\ b = -\frac{4}{\ln\frac{\Delta_s(4)}{\Delta_s(0)}} \tag{19}$$

with Δ_s according to (17), (15) and (16). Comparing these formulas shows that *a* and *b* only depend on the repetition frequencies f_{rep1} and f_{rep2}. Therefore, the exponential correction function for Δ_s has to be calculated just one time and can be used for all measurements of one EUT. Without using this exponential fitting function it would be necessary to evaluate the mentioned three formulas for each frequency of the spectrum.

4. Procedure for 2 pulses and quasi-peak detector

Now the procedure for the measurement of two pulses is complete. First, the parameters a and b of the correction function are calculated by evaluating equation (19).

After calculating the separately attenuated spectra, the superposition u_s of the two levels u'_1 and u'_2 (gray box in Fig. 5) can be calculated by

$$\begin{aligned} u_S &= \max(u'_1,\ u'_2) + \Delta_s \\ &= \max(u'_1,\ u'_2) + a \cdot e^{-\frac{|u'_1 - u'_2|}{b}} \end{aligned} \tag{20}$$

That means, at each frequency of the spectrum the correction value Δ_s as a function of the difference of the two levels (and the constant parameters a and b) is added to the higher of the two levels.

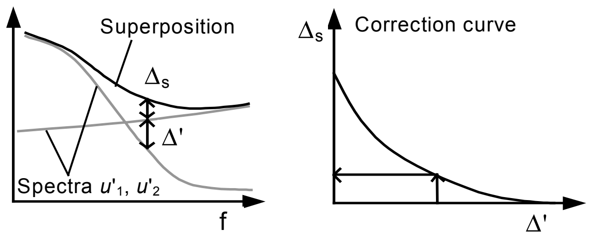

Fig. 16: Superposition of the separately attenuated spectra

The procedure allows the measurement of a signal that consists of two pulses (and of course narrow-band signals). Generally, it is possible to calculate also the superposition of more than two pulses by applying this procedure step by step to pairs of pulses. However, this does not make sense in reality, because it is very difficult to measure more than two pulses separately with the oscilloscope.

5. Example for the quasi-peak procedure

For the same EUT that was used in chapter 2.3 (peak detector), Fig. 17 presents the comparison of FEMIT and the test receiver for the described quasi-peak procedure.

The differences are (apart from the different noise level) less than 2 dB. The pulses had both the repetition frequency 100 Hz. This results in the correction function $3.0 \cdot e^{-\Delta'/5.2}$.

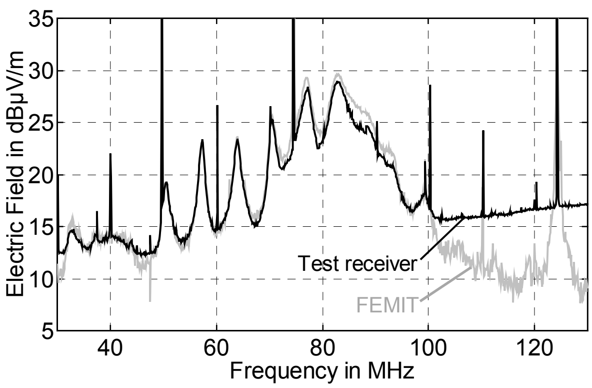

Fig. 17: Example for quasi-peak detector: FEMIT and test receiver results (same signal as peak detector example Fig. 8)

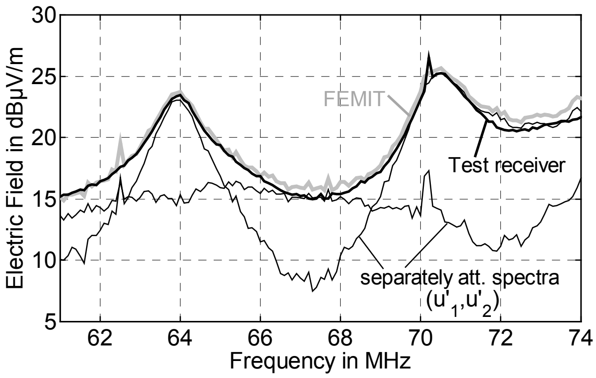

Fig. 18: Zoom into previous figure

The last figure shows a zoom view of Fig. 17. Here, the effect of the correction can be seen well: when the difference between the separately attenuated curves is high (f = 64 MHz, f > 70 MHz), the corrected FEMIT result is near the higher of the attenuated curves. When the difference is zero, the result is 3 dB higher ($3.0 \cdot e^{-\Delta'/5.2} = 3$ for $\Delta' = 0$).

6. Limits

The described procedures show good results, when the signal consists of narrow-band parts and one or two regular pulses. If more pulses (with significant influence on the spectrum) are present or the periods are not constant (e.g. brush discharge of a motor), errors can occur. In this case, a different (later presented) approach has to be used.

7. Conclusions

In this paper, the time domain emission measurement system FEMIT was described. FEMIT is an adequate measuring system especially for quick previews, repeated checks of the emission of an EUT and short phenomena.

The central results of the here presented aspects are:

- An advanced procedure allows the correct measurement of the *superposition of two pulses* (including narrow-band signals).
- The correction procedure depends on the simulated detector. Procedures for the peak, quasi-peak and average detector were described.
- Though the quasi-peak detector shows strong non-linear behaviour, a correction by a simple procedure is possible.

8. References

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