

MATLAB/Octave function to evaluate time-domain signals according to the measurement bandwidth and average/peak detector of EMI test receivers

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1 Introduction and motivation

Electromagnetic emissions are often measured with EMI (electromagnetic emissions) test receivers or spectrum analyzers [1] that must be specifically set up regarding their measurement bandwidth, frequency step size and measurement time (e.g. [2] for automobiles). Additionally, the emissions must be evaluated by different measurement detectors (e.g. average or peak) that may all have individual limit lines like in [2].

EMI measurements can be done in frequency or in time domain [1]. Frequency-domain measurement devices sequentially apply the superheterodyne principle to the frequencies of interest [3]. Since the measurement time for each frequency may take up to several seconds, the total measurement time can become long and cumbersome [4]. To overcome this problem, the time-domain signal can be processed by using, e.g., fast Fourier transforms (FFTs) and further methods [4]. This principle can also be applied to evaluate time-domain simulation results according to EMC standards. There are numerous publications on this topic including, e.g., [4] and [5].

In this contribution, a MATLAB/Octave function is presented that evaluates time-domain signals according to EMC standards. This “virtual EMI test receiver” mimics actual EMI test receivers regarding their measurement bandwidth, frequency step and average/peak detection. Potential use cases include the EMC evaluation of oscilloscope measurements or simulation results. The developed function can be found in the MATLAB Central (<https://mathworks.com/matlabcentral/>) under the title “Virtual EMI test receiver” by Andreas Bendicks [6].

In the following section, the superheterodyne measurement principle is described that is mimicked by the virtual EMI test receiver. Afterward, the corresponding signal processing of the MATLAB/Octave function is explained. The precision of the MATLAB/Octave function is verified by comparing its results to the ones of an actual EMI test receiver. The work is closed by a conclusion and an outlook.

2 Basics of the superheterodyne measurement principle

In reference to [7], the superheterodyne measurement principle is illustrated by some functional blocks and an exemplary signal in Figure 1. The input signal consists of an amplitude-modulated sine wave superposed with noise. In the superheterodyne measurement principle, the measurement is done one after another for all frequency points of interest. The frequency-selection is done by applying a band-pass filter with a specific resolution bandwidth (RBW). Since the band-pass filter (in the following also called “RBW filter”) is fixed to an intermediate frequency, the input signal’s frequency of interest must be shifted to this intermediate frequency. This is done by applying a mixer and a local oscillator. In the example of Figure 1, the carrier frequency of the amplitude-modulated sine wave is shifted to the intermediate frequency. Due to the RBW filter, the noise is mostly filtered out and the amplitude-modulated sine wave remains. The envelope of the

signal is found by an envelope detector. The envelope signal is low-pass filtered with the **video bandwidth (VBW)** to reduce noise on the instrument screen. At last, the peak and/or average detector is applied. The peak detector searches for the highest value of the envelope signal. The average detector determines the mean value of the envelope. This is the fundamental measurement principle that is reproduced by a MATLAB/Octave function in the following.

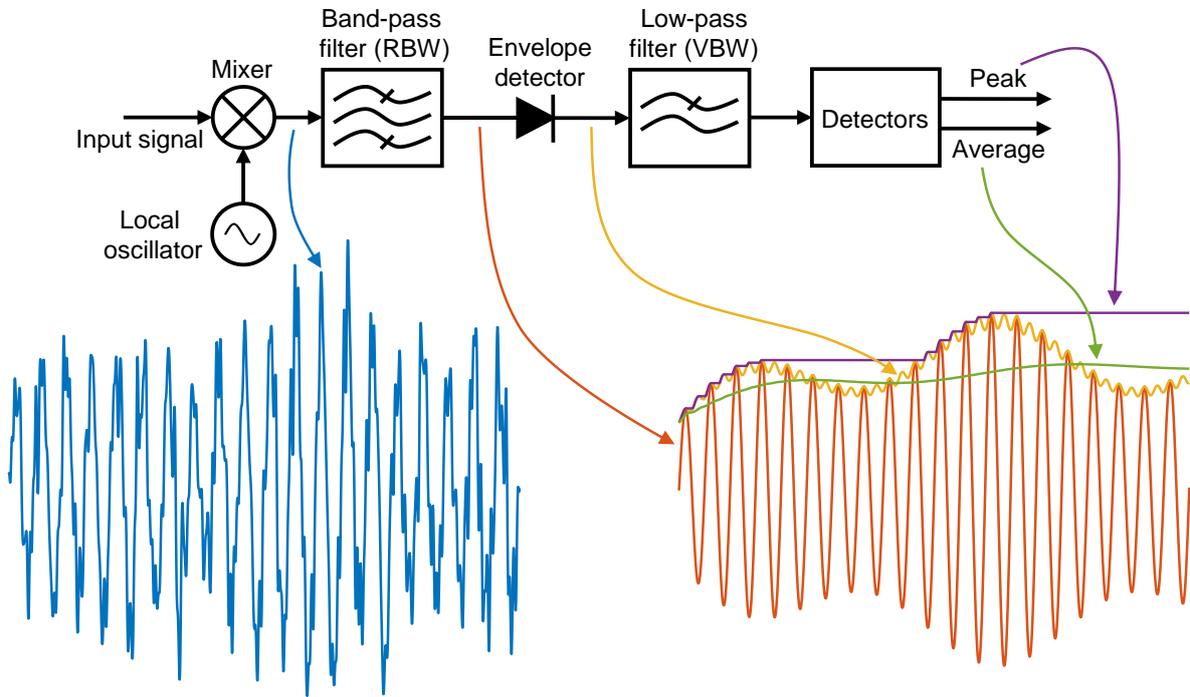


Figure 1: Illustration of the superheterodyne measurement principle [7].

3 Signal processing of the MATLAB/Octave function

In the following, an overview of the signal processing of the developed MATLAB/Octave function is given. At first, the in- and outputs of the function are stated. Then, an overview of the complete calculation procedure is given. Afterward, chosen steps are discussed in more detail. The provided code of the MATLAB/Octave function is widely commented to make it accessible.

3.1 Inputs

The MATLAB/Octave function requires the following inputs:

- Time vector of the input signal
- Amplitude vector of the input signal
- **Resolution bandwidth (RBW)** to be used
- Start frequency for the spectrum to be determined
- Stop frequency for the spectrum to be determined
- Frequency step for the spectrum to be determined
- Input option to immediately plot the found spectra
- Input option to get feedback in the command window (e.g. warnings or information on the current processing step)

The signal processing of the virtual EMI test receiver is fundamentally based on an FFT of the input signal. For reliable FFT results, the input signal must be given in such way that it could be periodically repeated. Furthermore, the time vector of the input signal must have a fixed time step.

The developed function interpolates the signal if this requirement is not fulfilled.

In practical EMI test receivers, the measurement time is an important parameter that defines how long the measurement is done at a single frequency point [2]. There are two requirements for the measurement time:

- 1) The measurement time must be set so long that the EMI test receiver “sees” the whole signal at least once (assuming the input signal has some form of periodicity).
- 2) The measurement time must be set so long that the analog circuits (e.g. the RBW filter) of the EMI test receiver have enough time to settle for each frequency point.

Given that the input signal of the virtual EMI test receiver is periodic, it always evaluates at least one period of the signal. The FFT-based signal processing of the virtual EMI test receiver has no settling times that could affect the measurement time. So, the two requirements for the measurement time are intrinsically fulfilled as long as the input signal is periodic. Therefore, it is not required to further include a measurement time in the MATLAB/Octave function. If a specific measurement time must be considered (e.g. in regard to EMC standards), it can be respected by using a respectively long time window of the input signal.

3.2 Outputs

The MATLAB/Octave function determines the spectrum of the input signal by using the above parametrizations. It returns the following data:

- Frequency vector for the average- and peak-detected spectrum
- Amplitude vector of the average-detected spectrum
- Amplitude vector of the peak-detected spectrum
- Frequency vector of the internal FFT
- Complex amplitude vector of the internal FFT
- Figure with the found spectra if the respective input option is set
- Feedback in the command window if the respective input option is set

3.3 Structure chart of the function

The fundamental structure of the function can be found in Figure 2.

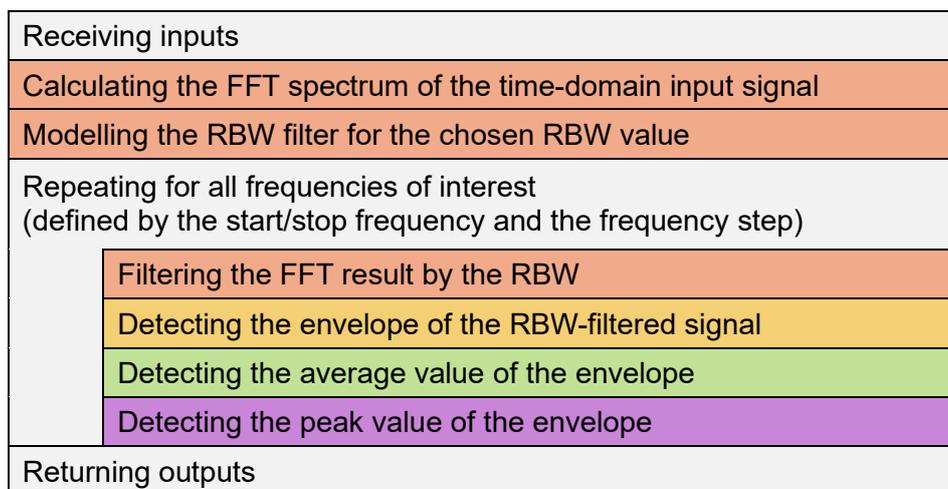


Figure 2: Structure chart of the MATLAB/Octave function (the colors refer to the ones in Figure 1).

At first, the function receives its inputs. It calculates the FFT spectrum of the time-domain input signal. Afterward, the RBW filter is modelled for the given RBW value. In the following loop, each frequency is individually processed. The FFT spectrum is filtered by the RBW for the current frequency. This RBW-filtered signal is further processed to detect the corresponding envelope. The information of the envelope is used to determine the average and peak values for the current frequency point. After repeating this signal processing for all frequencies of interest, the function returns its outputs.

3.4 Calculating the FFT spectrum

It is assumed that the input signal $x_{\text{input}}(t)$ is periodic to the given time window T_0 . Note that the signal is denoted by an 'x' since it can be a voltage or a current. Applying an FFT results in a spectrum $X_{\text{input}}(kf_0)$ of discrete harmonics (at multiples of $f_0 = 1/T_0$) with complex amplitudes. The FFT returns the two-sided spectrum with positive and negative frequencies. Here, the one-sided spectrum (that only contains positive frequencies) is used. The complex amplitudes of the negative frequencies are respected by adding them to the respective positive ones. The DC component (for $k = 0$) is omitted since it is not required for the further signal processing.

3.5 Modelling the RBW filter

The RBW filter is modeled by using a Gaussian function [8]:

$$H_{\text{RBW}}(f) = \exp[-b \cdot (f - f_{\text{center}})^2] \quad (1)$$

The magnitude response of the RBW filter is 1 ($\triangleq 0$ dB) at its center frequency f_{center} . The following requirement must be fulfilled [1]:

$$H_{\text{RBW}}\left(f = f_{\text{center}} \pm \frac{\text{RBW}}{2}\right) \stackrel{!}{=} 0.5 \quad (\triangleq -6 \text{ dB}) \quad (2)$$

$$\Rightarrow \exp\left[-b \cdot \left(\pm \frac{\text{RBW}}{2}\right)^2\right] = 0.5 \quad (3)$$

$$\Rightarrow b = -\ln(0.5) \cdot \frac{4}{\text{RBW}^2} \quad (4)$$

So, the RBW filter is modeled by:

$$H_{\text{RBW}}(f) = \exp\left[4 \cdot \ln(0.5) \cdot \left(\frac{f - f_{\text{center}}}{\text{RBW}}\right)^2\right] \quad (5)$$

3.6 RBW-filtering the FFT result for the current frequency point

In this mathematical solution, it is not required to use a local oscillator and a mixer to shift the input signal to the RBW filter. Instead, the RBW filter can easily be shifted onto the signal. To filter the input signal for a specific frequency f_{eval} (**evaluated**), the center frequency f_{center} of the RBW filter is shifted to this value. The FFT harmonics are filtered for the frequency f_{eval} by:

$$X_{\text{filtered}}(kf_0, f_{\text{eval}}) = H_{\text{RBW}}(kf_0 - f_{\text{eval}} + f_{\text{center}}) \cdot X_{\text{input}}(kf_0) \quad (6)$$

By doing so, harmonics close to f_{eval} are passed with only little attenuation. Harmonics with higher and lower frequencies are increasingly dampened.

3.7 Detecting the envelope for the current frequency point

The envelope of the RBW-filtered signal is found by using a Hilbert transform. The Hilbert transform of $X_{\text{filtered}}(kf_0, f_{\text{eval}})$ directly follows from a multiplication with $-j = -\sqrt{-1}$ (note $k \geq 1$ due to the one-sided spectrum and the omission of the DC component):

$$X_{\text{filtered,Hilbert}}(kf_0, f_{\text{eval}}) = -j \cdot X_{\text{filtered}}(kf_0, f_{\text{eval}}) \quad (7)$$

Afterward, the corresponding time-domain signals $x_{\text{filtered}}(t, f_{\text{eval}})$ and $x_{\text{filtered,Hilbert}}(t, f_{\text{eval}})$ are found by applying an inverse fast Fourier transform (IFFT). The envelope can be found by calculating the Pythagorean sum of the two signals:

$$x_{\text{envelope}}(t, f_{\text{eval}}) = \sqrt{x_{\text{filtered}}^2(t, f_{\text{eval}}) + x_{\text{filtered,Hilbert}}^2(t, f_{\text{eval}})} \quad (8)$$

3.8 Detecting the average value for the current frequency point

Like for practical EMI test receivers, the average value $X_{\text{output,average}}(f_{\text{eval}})$ is determined by the mean value of the envelope $x_{\text{envelope}}(t, f_{\text{eval}})$:

$$X_{\text{output,average}}(f_{\text{eval}}) = \text{mean}\{x_{\text{envelope}}(t, f_{\text{eval}})\} \quad (9)$$

3.9 Detecting the peak value for the current frequency point

For the peak value $X_{\text{output,peak}}(f_{\text{eval}})$, the highest value of the envelope $x_{\text{envelope}}(t, f_{\text{eval}})$ is determined:

$$X_{\text{output,peak}}(f_{\text{eval}}) = \max\{x_{\text{envelope}}(t, f_{\text{eval}})\} \quad (10)$$

4 Verification with a real EMI test receiver measurement

To verify the designed MATLAB/Octave function, a comparison with a real EMI test receiver is done. As a test signal, a **pulse-width modulation (PWM)** signal is generated by an arbitrary waveform generator. It has a switching frequency of 100 kHz and a voltage range of ± 0.5 V at a 50 Ω termination. Its duty cycle is varied between 10 % and 90 % in a sinusoidal manner with a fundamental frequency of 200 Hz. As a reference, this signal is measured in the frequency range from 150 kHz to 30 MHz with an ESRP EMI test receiver from Rohde & Schwarz. According to [2], it is set up with an RBW of 9 kHz, a frequency step of 2.25 kHz and a measurement time of 50 ms. Additionally, the PWM signal is measured for 50 ms with an oscilloscope with a sampling rate of approximately 200 MS/s and a sufficiently large bandwidth. The signal acquired by the oscilloscope is processed by a PC using the developed MATLAB/Octave function with the same parameters as the ESRP EMI test receiver. The results are discussed in the following.

In Figure 3, the calculated and measured spectra around the second switching harmonic (at 200 kHz) are compared. The average and peak spectra are practically the same for the MATLAB/Octave function and the actual EMI test receiver. The deviations are below 0.5 dB at 200 kHz. The average noise floor (below 180 kHz and above 220 MHz) of the MATLAB/Octave result appears to be higher than the one of the actual EMI test receiver. It is assumed that this effect is due to the noise floor of the used oscilloscope. For analysis purposes, the FFT result is also given. The switching harmonic at 200 kHz has the highest value. There are numerous sideband harmonics around it due to the modulation of the PWM signal [9].

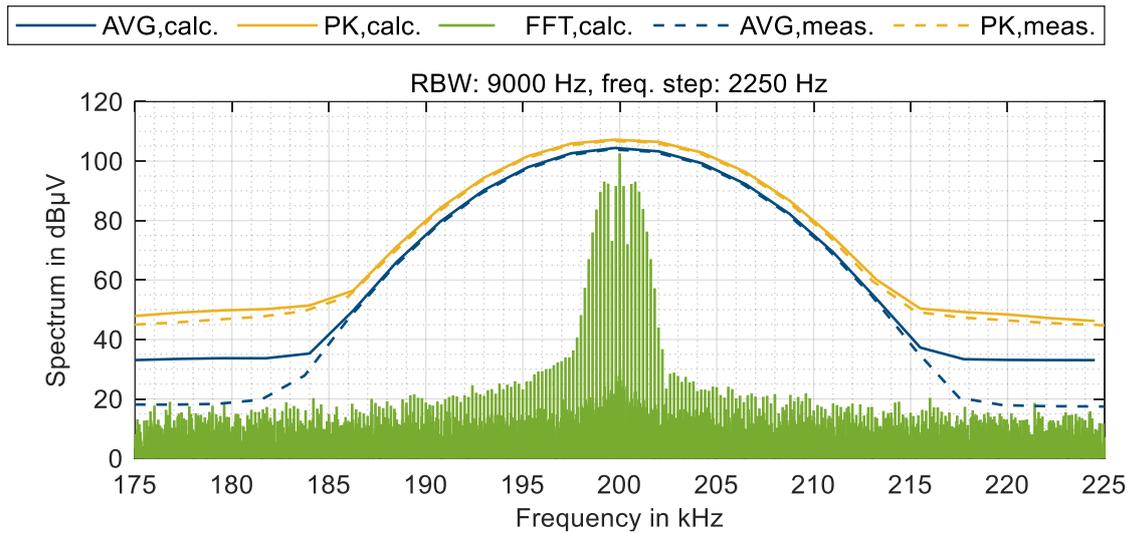


Figure 3: Comparison of calculated and measured spectra around 200 kHz.

In Figure 4, the switching harmonics at 2.4, 2.5 and 2.6 MHz are depicted. Here, the levels at the switching harmonics deviate by less than 1 dB. In the FFT result, it can be seen that the switching harmonics are still dominant. However, the sidebands become wider due to the higher order of the switching harmonics.

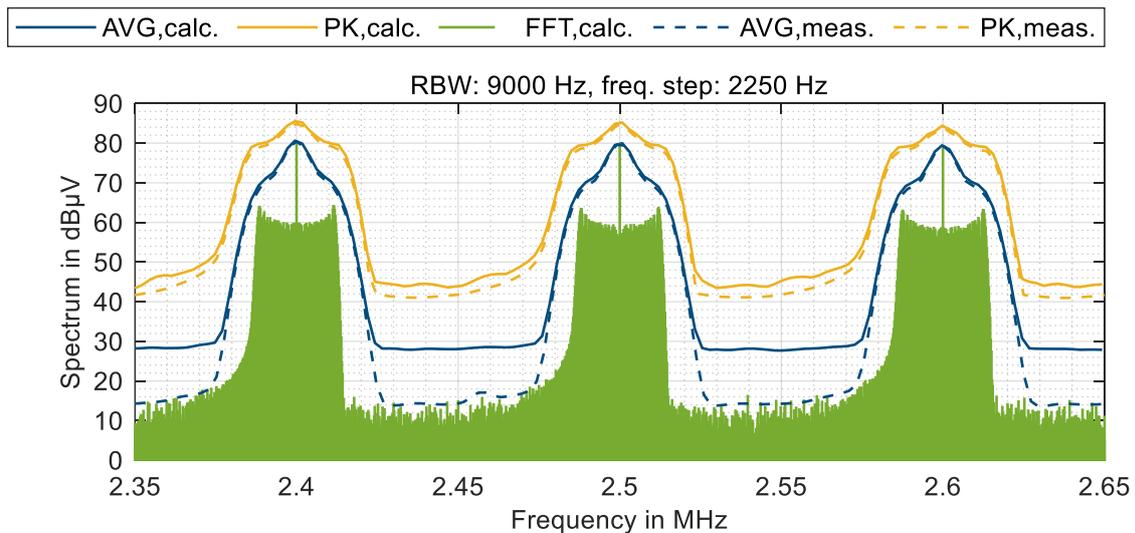


Figure 4: Comparison of calculated and measured spectra around 2.5 MHz.

In Figure 5, the switching harmonics at 28.9, 29.0 and 29.1 MHz are shown. It can be found that the differences between the peak spectra are larger than for lower frequencies. For the switching harmonic at 29 MHz, the calculated peak value deviates by approximately 4.5 dB.

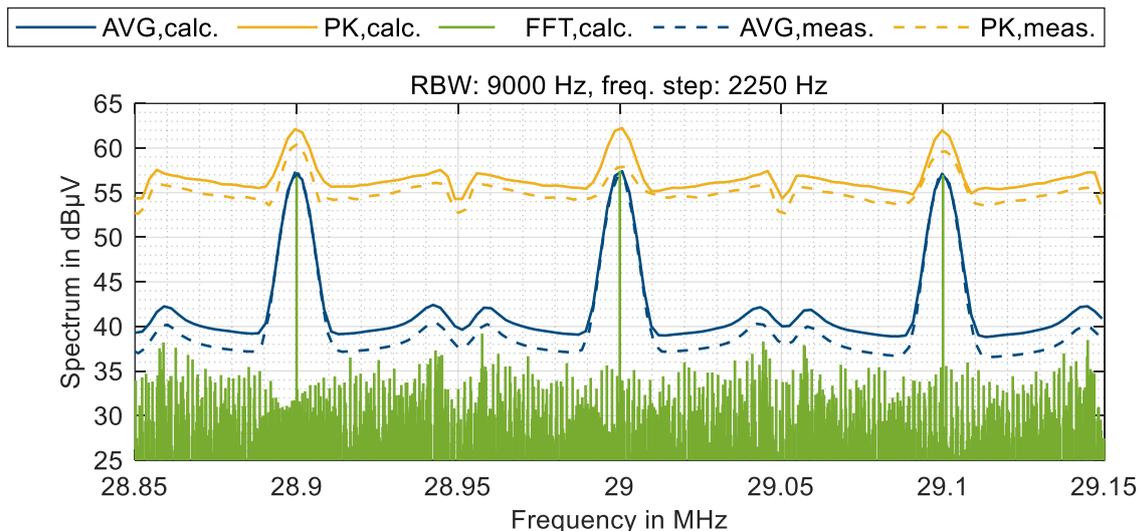


Figure 5: Comparison of calculated and measured spectra around 29 MHz.

Considering the complete frequency range from 150 kHz to 30 MHz, the calculated average values of the switching harmonics deviate by less than 2 dB from the actual EMI test receiver. The calculated peak values of the switching harmonics deviate by less than 5 dB.

5 Conclusion and outlook

In this work, a MATLAB/Octave function has been developed for calculating the average and peak spectra as displayed on an EMI test receiver. The input for this function is a time-domain signal from a measurement or simulation. The source code is provided for public usage via the MATLAB file exchange website [6].

A comparison to an actual EMI test receiver shows that the calculated average values deviate by less than 2 dB for the characteristic peaks of the spectrum (i.e. the switching harmonics) for spectral frequencies of up to 30 MHz, the calculated peak values deviate by less than 5 dB.

The function gives good results for various test cases. However, the function should be further verified in the future. Apart from that, investigations could be done to find the root cause(s) for the deviations of the calculated and measured spectra. Furthermore, the quasi-peak detector should be added.

Literature

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