

Modulation analysis in ArtemiS SUITE¹

Modulation analysis of ArtemiS SUITE delivers the envelope spectra of partial bands of an analyzed signal. This allows to determine the frequency, strength and change over time of amplitude modulations in a signal. While the psychoacoustic parameters roughness and fluctuation strength allow only certain modulation frequencies to be examined and at the same time judged, a modulation analysis covers a wider frequency range, which also includes the roughness and fluctuation strength areas, and does not add psychoacoustic weightings.

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Amplitude modulation

A continuous sound, whose amplitude varies sinusoidally around a mean value $\hat{p}_{\text{carrier}}$, is called a sinusoidally amplitude-modulated signal. The sound pressure $p_a(t)$ of such a sine tone is calculated with the following formula: $p_a(t) = \hat{p}_{\text{carrier}} \cdot (1 + m \cdot \sin(2\pi f_{\text{mod}} \cdot t)) \cdot \sin(2\pi f_{\text{carrier}} \cdot t)$

f_{mod} : modulation frequency
 f_{carrier} : carrier frequency
 m : modulation depth

For a non-sinusoidal amplitude modulation, the first sine function in the formula must be replaced. Replacing the second sine changes the shape of the carrier signal.

The modulation depth m describes the strength of the modulation and is calculated as the ratio of alternating component to constant component of the signal.

Figure 1 shows a schematic representation of a sinusoidally amplitude-modulated signal.

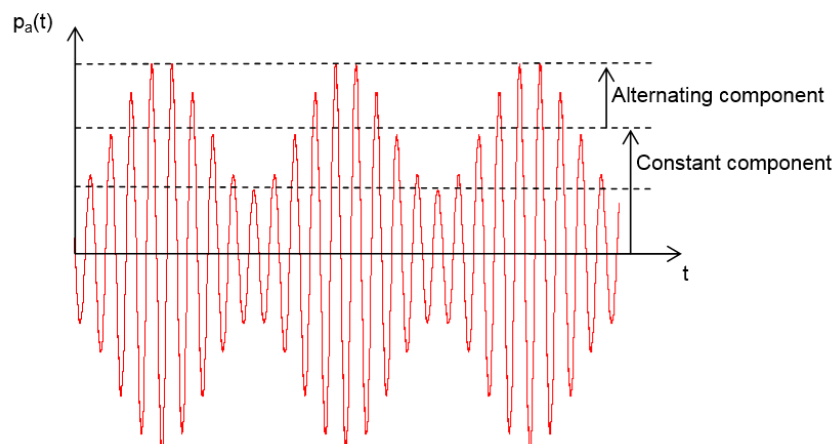


Figure 1: Schematic representation of an amplitude-modulated sine tone

¹ The descriptions in this Application Note refer to version 9.2. The general procedures also apply to other versions. However, the scope of functionality and the user interface may differ.

Modulation analysis in ArtemiS SUITE

ArtemiS SUITE provides several different analysis functions to examine the modulation of signals.² The following table lists and explains these functions.

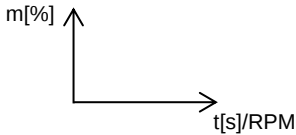
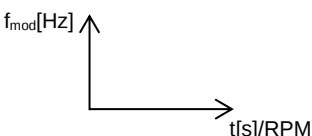
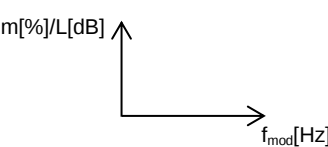
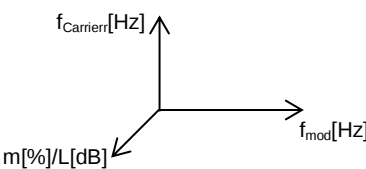
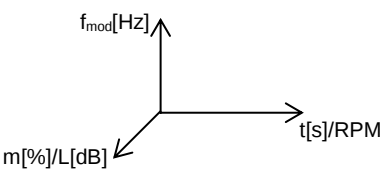
Analysis	Description
Degree Of Modulation vs. Time / RPM	2D analysis of the degree of modulation of a selectable frequency range over time or RPM 
Modulation Frequency vs. Time / RPM	2D analysis of the modulation frequency of a selectable frequency range over time or RPM 
Modulation Spectrum	2D analysis of the average modulation factor of a selectable frequency range over the modulation frequency 
Modulation Spectrum vs. Band	3D analysis of the modulation factor over the modulation and carrier frequency 
Modulation Spectrum vs. Time / RPM	3D analysis of the modulation factor of a selectable frequency range over time or RPM and the modulation frequency 

Table 1: Description of the different modulation analyses in ArtemiS SUITE

In the Properties window of each analysis, the setting for calculating the modulation can be selected. The configurable parameters for all of the analysis functions listed above are very similar. Figure 2 shows the Properties window of the **Modulation Spectrum vs. Time** analysis. This analysis has the most comprehensive Properties window and is explained in detail in the following.

² The modulation analyses can only be selected in ArtemiS SUITE if a license including ASM 17 is used. For RPM depending modulation analyses ASM 13 is needed additionally.

Figure 2: Properties window of the *Modulation Spectrum vs. Time* analysis

In the upper part of the Properties window, you determine the type, bandwidth and position of a filter. Select these parameters in such a way that the signal component to be examined for modulation lies within this filter band³:

In the first selection box, you select the **Band Type**. The available band types are **Standard Band**, **Fixed Band**, and **Tracking Band**.

If **Standard Band** is selected, you can also specify the width of the frequency band to be used with the **Bands** parameter. The available settings are **1/3 Octave**, **Octave**, **Critical Bands** and **Full Bandwidth**. Furthermore, you define the position of the desired frequency band with the selection boxes **Row** and **Band Number**. With setting **A**, the frequency bands are distributed in such a way that the 1 kHz mark corresponds to the cutoff frequency of one filter. With setting **B**, however, the bands are distributed in such a way that the 1 kHz mark corresponds to the center frequency of one filter. Thus, by means of settings **A** and **B**, the filters can be shifted by half of the bandwidth against to each other.

If **Fixed Band** is selected, the desired frequency band must be specified by **Frequency** and **Quality**.

In case of **Tracking Band**, the parameters to be specified are **Tracking Order** and **Quality**.

In the lower part of the Properties window, the field **Envelope Lowpass [Hz]** allows the maximum frequency of the filter envelope to be specified. The cut-off frequency of the filter should be set slightly higher than the modulation frequency, up to which the analysis is to be calculated.

Furthermore, the parameters for the FFT analysis of the envelope must be specified: **Spectrum Size**, **Window Function** and **Overlap [%]**.

By selecting the **Degrees of Modulation** option, the result can be displayed as modulation factor with the unit %. If this option is deactivated, the signal level of the envelope is displayed directly.

The Properties window of the other modulation analyses resemble the one described above, but with less configuration options. For example, the **Degree of Modulation vs. Time** analysis does not have the **Degrees of Modulation** checkbox, since this analysis always determines the degree of modulation in percent.

³ If you want to examine the entire frequency range of a signal, you can use the 3D analysis **Modulation Spectrum vs. Band**.

Application examples

Figure 3 shows the different modulation analysis results of a sound signal generated by a combustion engine at idle speed. In addition, a time-dependent FFT analysis is shown.

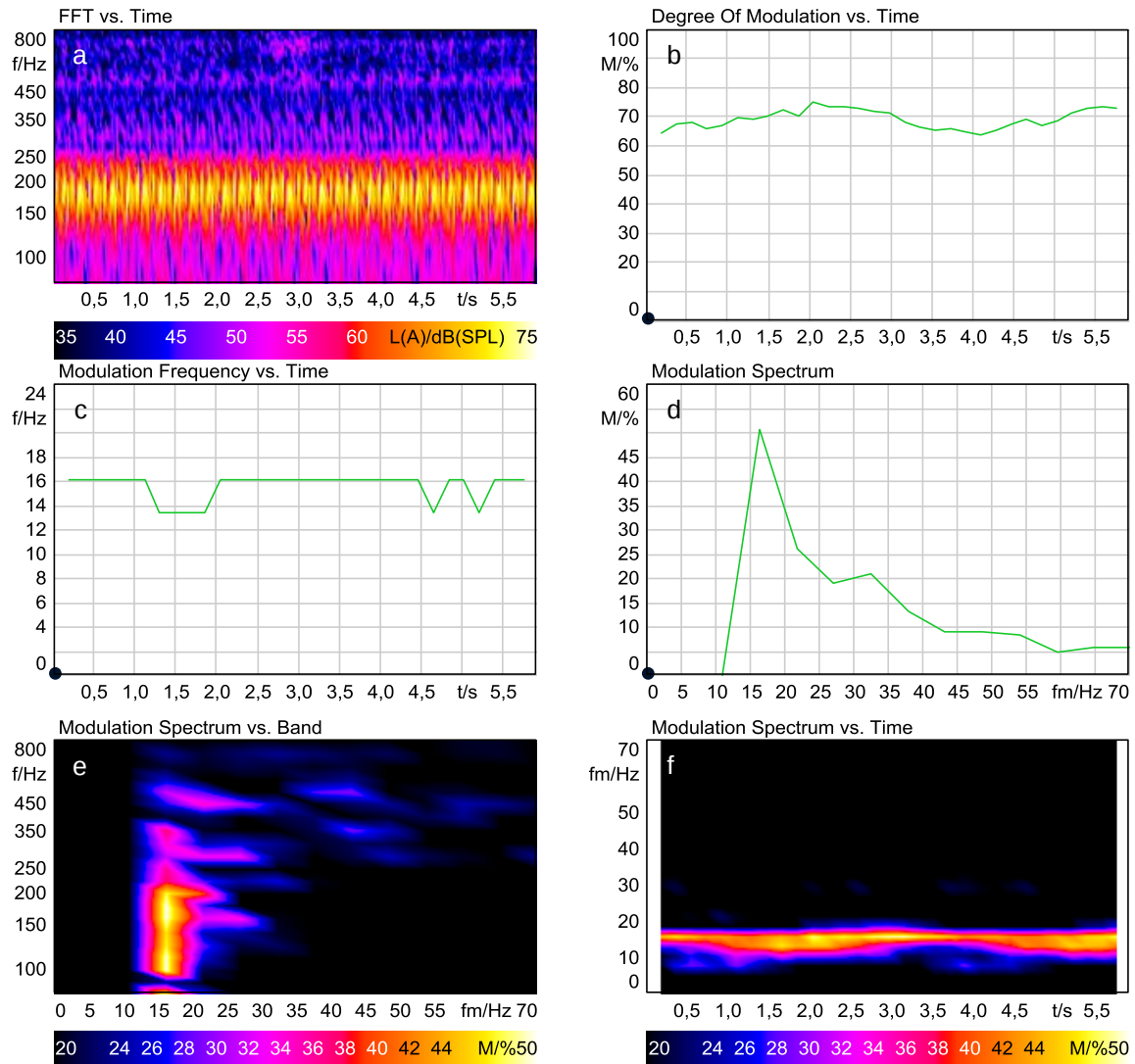


Figure 3: a) *FFT vs. Time*, b) *Degree of Modulation vs. Time*, c) *Modulation Frequency vs. Time*, d) *Modulation Spectrum* of the octave band around 180 Hz, e) *Modulation Spectrum vs. 1/3-octave bands*, f) *Modulation Spectrum vs. Time* of the octave band around 180 Hz

The result of the FFT-analysis (figure 3a) shows that the frequency band between 140 and 200 Hz is significantly modulated. Therefore, for those modulation analysis functions that require a certain frequency band to be specified by the user, the octave band around 180 Hz (125 to 250 Hz) was selected. For the **Modulation Spectrum vs. Band** analysis, a subdivision into 1/3-octave bands was chosen.

Figure 3b shows the result of the **Degree of Modulation** analysis. The octave band around 180 Hz is modulated with a degree of modulation of about 70 %. The degree of modulation is relatively constant across the entire duration of the signal. Figure 3c shows that the signal is modulated mainly with a modulation frequency (or rate) of approximately 16 Hz. This can also be seen in figure 3d, where the modulation frequencies and the corresponding modulation factor are displayed for the octave band around 180 Hz. This figure also shows that the signal is modulated with other frequencies as well. However, the degree of modulation for these modulation frequencies is significantly lower than for the 16 Hz modulation frequency. Figure 3e shows a spectrogram to illustrate which carrier frequency is

modulated with which modulation frequencies. The color indicates the strength of the modulation. Again, this diagram shows that the most significant modulation frequency is approximately 16 Hz. The history of the modulation frequency and the degree of modulation over time is shown in figure 3f. Since the selected sound example is almost constantly modulated over the entire signal duration, this diagram shows only a small temporal variation.

Figure 4 shows the modulation analysis results of a sound recorded in a vehicle cabin at about 3000 RPM.

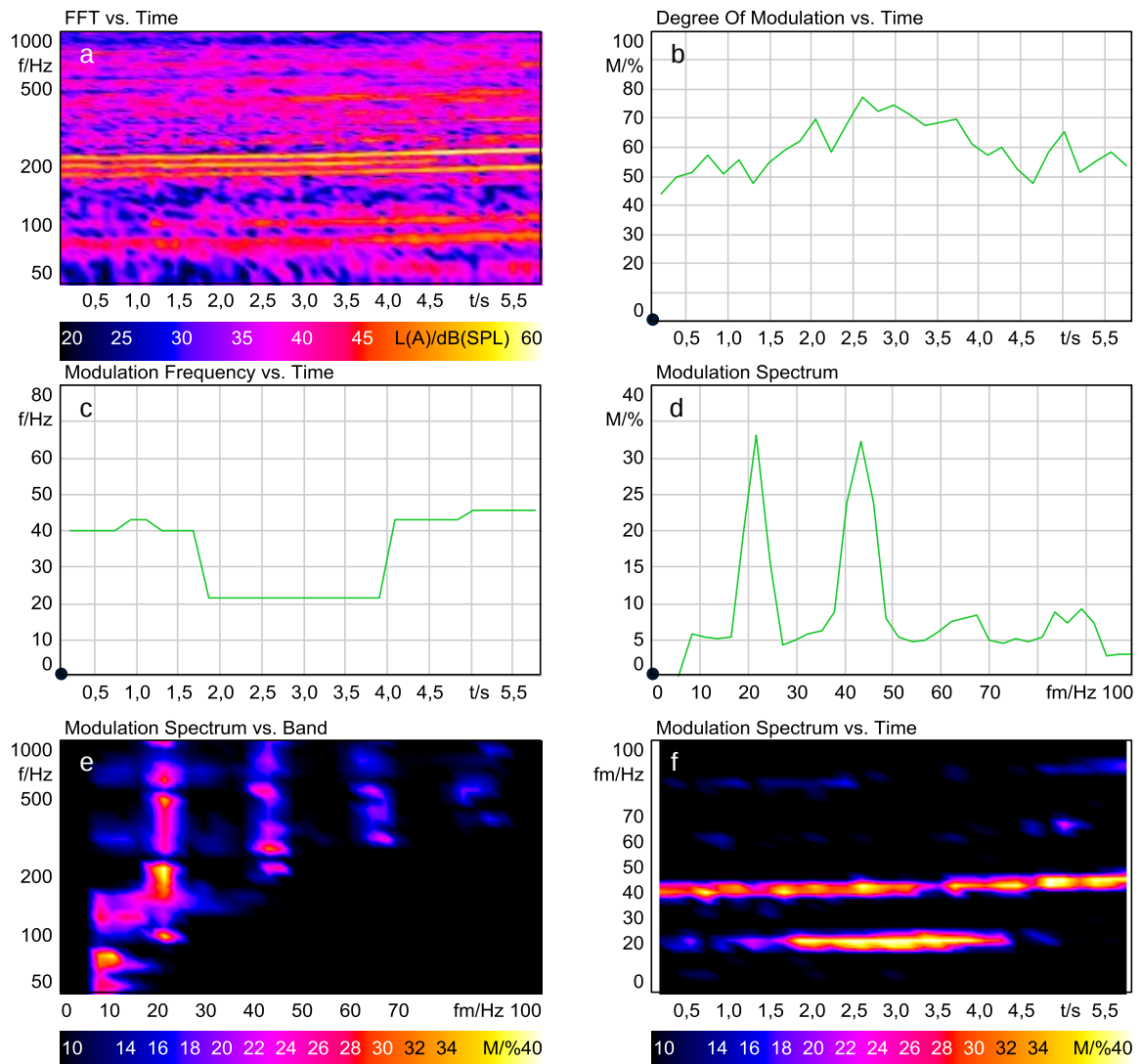


Figure 4: a) **FFT vs. Time**, b) **Degree of Modulation vs. Time** of the octave band around 250 Hz, c) **Modulation Frequency vs. Time** of the octave band around 250 Hz d) **Modulation Spectrum** of the octave band around 250 Hz, e) **Modulation Spectrum vs. 1/3-octave bands**, f) **Modulation Spectrum vs. Time** of the octave band around 250 Hz

The **FFT vs. Time** analysis (figure 4a) shows that individual engine orders clearly stand out in the signal. The distance between the three loudest orders is approximately 20 Hz. Therefore, the modulation analysis shows maxima at the modulation frequency of approximately 20 Hz and the corresponding harmonics. For the analyses 4b, 4c, 4d, and 4f, the octave band around 250 Hz was examined.

These modulation frequencies between 20 and 45 Hz are often found in the interior noise of vehicles and can be reliably detected and displayed with the various modulation analyses of ArtemiS SUITE.

Summary

If it is found that a signal is modulated, for example, by viewing an **FFT vs. Time** analysis or by listening to the signal, the first step that makes sense in most cases is a **Modulation Spectrum vs. Band** analysis. The result of this analysis provides an overview of the modulation frequencies in the entire frequency range. Furthermore, the degree of modulation is shown as well. If the user already knows which signal frequency range might contain modulations, the **Modulation Spectrum** analysis is useful. This analysis determines the modulation factor and modulation frequency of a certain specified frequency range of the input signal. This analysis can be used, for example, for quality tests if a product has a known fault that expresses itself in modulations in a certain frequency range.

For analysis of signals that change rapidly over time, the time- or RPM-dependent analysis functions (**Degree of Modulation vs. Time/RPM**, **Modulation Frequency vs. Time/RPM**, **Modulation Spectrum vs. Time/RPM**) are recommended. These methods can show variations of the modulation. One possible application is modulation analysis of a sound recording of an engine run-up. For the analysis of signals containing RPM information, it is useful to employ order filters rather than frequency-dependent filters. The filter type can be selected in the Properties window of the respective analysis.

Due to the various modulation analyses provided by ArtemiS SUITE, you are always in a position to carry out the appropriate examination for each of your sound signals.

Do you have any questions or comments?

Please write to imke.hauswirth@head-acoustics.de.

We look forward to receiving your feedback!

Appendix

Frequency modulation

If the frequency of a signal is modulated rather than the amplitude, this is called a frequency-modulated signal. The left image in figure 5 shows the FFT vs. time analysis of a frequency-modulated sine tone. Such a signal can be examined with the modulation analysis functions provided by ArtemiS SUITE as well. However, this requires a very careful interpretation of the analysis results.

For the modulation analysis, the signal is divided into different frequency bands as already described above. Depending on the examined frequency range, the analysis yields different results. For a frequency-modulated signal, this is shown schematically in figure 5. When a frequency-modulated signal is divided into individual frequency bands, amplitude-modulated signals are created, which can then be examined with the modulation analysis functions in ArtemiS SUITE.

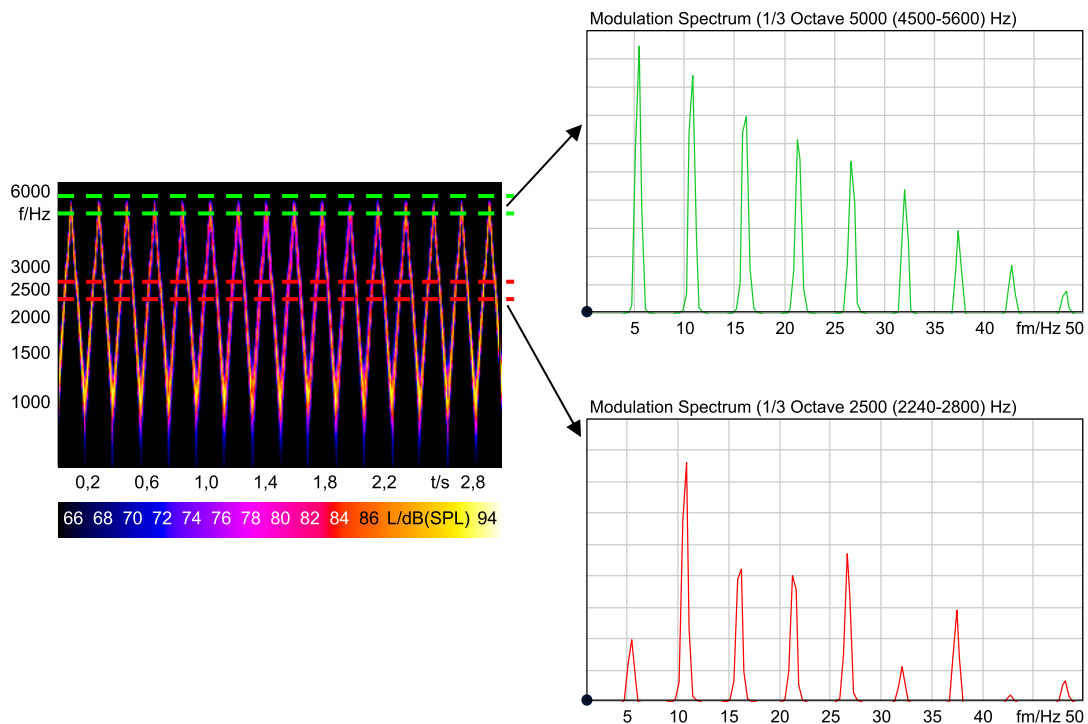


Figure 5: Modulation analysis of a frequency-modulated sine tone

The modulation frequency of the amplitude modulation equals the original frequency modulation or a multiple thereof. The modulation spectrum of the frequency range marked in green in figure 5 ($1/3$ octave around 5000 Hz) contains, as its main component, the modulation frequency of the frequency modulation of about 5.5 Hz. The analysis of the range marked in red ($1/3$ octave around 2500 Hz) shows a modulation frequency of about 11 Hz as its main component, i.e., twice the actual modulation frequency of the frequency modulation. In order to determine which frequency band is suitable for the modulation analysis of a frequency-modulated signal, it is recommended to always perform an **FFT vs. time** analysis in addition to the modulation analysis, to provide the required information for the interpretation of the modulation analysis results.

Calculation steps of the modulation analysis

As mentioned before, modulation analysis is the spectral analysis of the envelope of a signal. Figure 6 shows a schematic diagram of the procedure used in this analysis. Below the individual calculation steps are briefly explained.

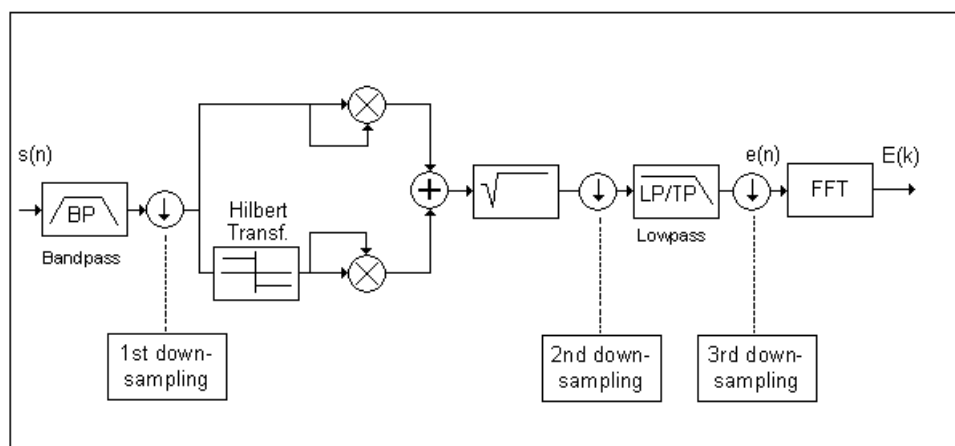


Figure 6: Schematic diagram of modulation analysis steps in ArtemiS SUITE

In the first step, the input signal is filtered with an IIR band-pass in order to extract the frequency range specified in the Properties window. An octave band, a 1/3-octave band, or a frequency group can be selected. A Butterworth filter of 4th order is used for filtering. If high frequency components were removed by this filtering, a first downsampling can be performed, because the sampling rate can be reduced depending on the selected frequency range.

This downsampling reduces the calculation time, but primarily it improves the quality of the subsequent Hilbert transformation. This transformation determines the imaginary part of the complex envelope from the input signal. The real part of the envelope is given by the input signal itself. In the next step, the actual envelope of the signal is calculated, which equals the absolute value of the complex envelope. This means that the squares of the real part (the band pass signal) and the imaginary part (the output signal of the Hilbert transformation) are added, and the square root is extracted from the result.

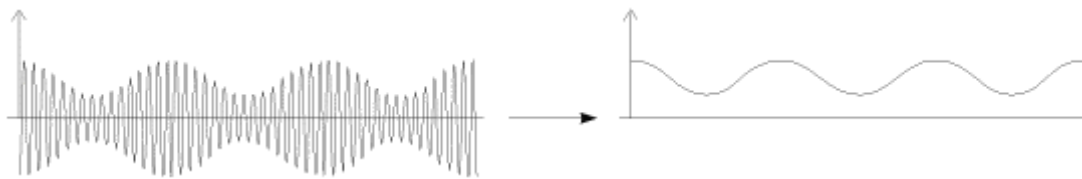


Figure 7: Determining the envelope

The envelope is then downsampled again according to the bandwidth of the selected frequency range, and filtered by a low-pass. This is done using a filter of 2nd order, whose cut-off frequency can be selected in the Properties window (**Envelope Lowpass [Hz]**). The selected frequency should be above the highest modulation frequency up to which the analysis is to be calculated. According to the cut-off frequency of this low-pass filter, the signal is then downsampled once more.

In the last step of the modulation analysis an FFT analysis of the envelope is performed. In the Properties window of the analysis, the user can specify the window function (**Window Function**), the window width (**Spectrum Size**) and the overlapping (**Overlap**) for the FFT analysis. These parameters can be used to influence, for example, the time and frequency resolution of the analysis.