

Order Analysis

Introduction

In the analysis of engine sounds, the rotational speed (revolutions per minute [rpm]) plays an important role: Certain sound emissions repeat with each revolution at a specific angle of rotation, which results in a spectral content that corresponds with the multiples of the rotational frequency.

Frequencies that correspond to the motor's rpm or multiples of it are called orders. The first order is identical with the frequency of the rpm; the second order is the frequency of the first order multiplied by the factor 2 etc. Order analysis is the process for determining the signal level or level curve for specific orders.

The levels in an order analysis can be represented in different ways: an average level value (figure 1a) or a level curve versus time (figure 1b/1d) or versus rpm (figure 1c/1e). ArtemiS can display either an order spectrum (figure 1d/1e) or the level curves of individual orders (figure 1b/1c).

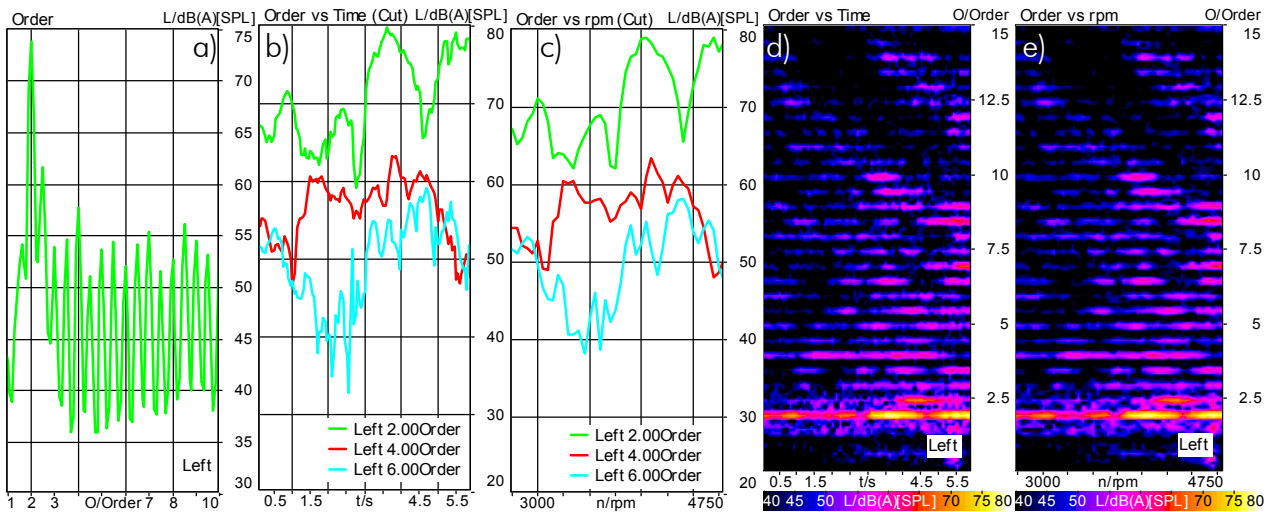


Figure 1: Different variants of order analysis

Figure 2 shows an order analysis compared to an *FFT vs. time* and an *FFT vs. rpm* analysis. The *FFT vs. time* analysis shows the level curve of a sound file versus time and frequency. The color coding of the spectrum allows the sound level to be read from the diagram both versus time (x-axis) and versus frequency (y-axis). Such a spectrum thus allows the viewer to determine the sound level at a certain time for a certain frequency. In the *FFT vs. rpm* analysis, the x-axis is used for rpm instead of time. That way the viewer can determine the sound level spectrum, which is generated at any given motor speed. Since the rpm of the sound file, used for this example, increases linearly with time, the results of the *FFT vs. time* analysis do not differ very much from those of the *FFT vs. rpm* analysis. In the *Order vs. rpm* analysis, the x-axis is used for

rpm, as it is in the *FFT vs. rpm* analysis. However, the y-axis no longer represents the frequency values in Hz, but instead the rotational frequency and its multiples, i.e. the orders. To achieve this, the frequency axis changes depending on the current rpm, so the orders no longer appear as curves, but as straight lines in the diagram. The diagram thus shows the dependency of the sound level on both the revolution rate and the order.

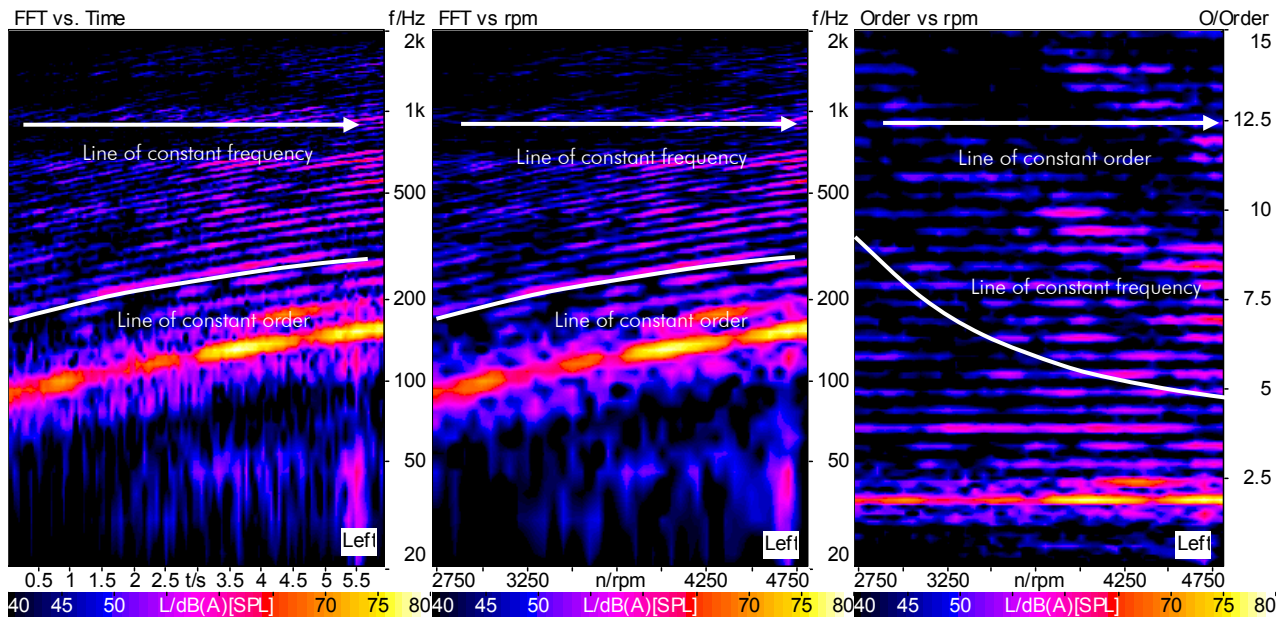


Figure 2: FFT vs. time, FFT vs. rpm and Order vs rpm

The following section contains a detailed description of the procedure used to calculate an order analysis. The first part discusses the calculation of an order spectrum that depends on the rpm and uses the *variable DFT length* method. The second part discusses the calculation of an order spectrum that uses the *rpm-synchronous Resampling* method. The various adjustment options in the *Properties* dialog for each of the analysis techniques are described along with the calculations of the level curves of individual orders (*Cut* function) and the averaged level analysis. Finally, the differences between the two calculation methods *Variable DFT Length* and *RPM-synchronous Resampling* will be explained.

Calculating an Order Spectrum vs. RPM with the “Variable DFT Length” Method

For rpm-dependent order analysis, the time signal is not analyzed continuously, but instead selectively at certain positions separated by constant revolution rate intervals. These intervals are defined in the *Properties* dialog of the order analysis under *Step (rpm)* (see figure 3). At these positions, a time interval ΔT , located symmetrically around each point, is analyzed with a DFT (Discrete Fourier Transform).

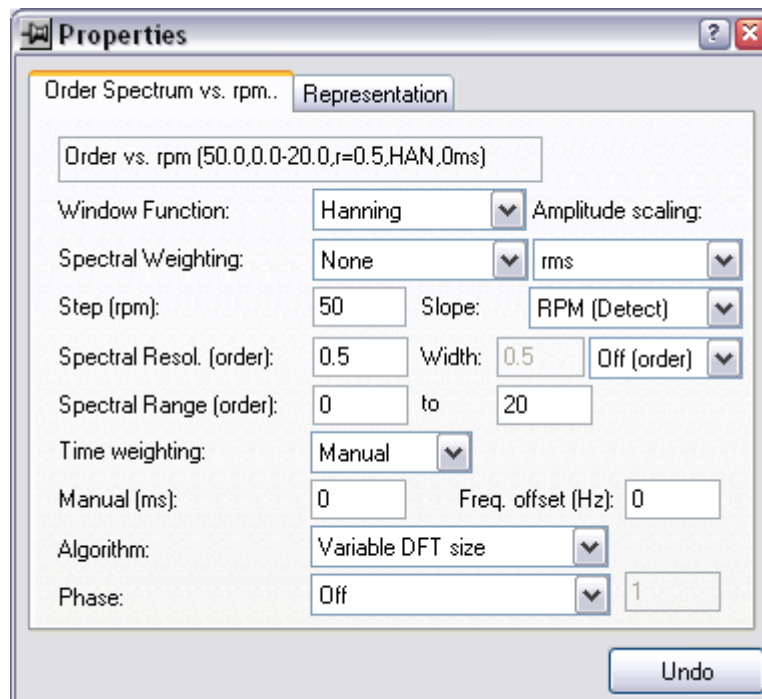


Figure 3: Properties dialog of the *Order Spectrum vs. RPM* analysis

If a step width of 50 rpm is selected for the analysis of a measurement that was started at 920 rpm, the first DFT analysis is performed at 950 rpm, provided that a time window of the length ΔT can be positioned around this value. The next sampling point is then at 1000 rpm etc.

Once the first sampling point has been found, all further DFTs are performed in the specified rpm step width. If a DFT has been calculated at 1500 rpm and the step width is set to 100 rpm, the next point in time for an analysis to be made is when the rotational speed is 1600 rpm. The exact time selected for the analysis is the point where the revolution rate reaches the value 1600 for the first time. If the rpms are not constantly increasing (or decreasing) and the value 1600 is reached again, this point will be ignored and only the first point where this rpm value is reached is used for the DFT analysis.

The order resolution is specified via the *Spectral Resolution (order)* value (also referred to as *order resolution*). Depending on the current revolution rate, this value simultaneously determines the current window length of the analysis and the time resolution ΔT respectively. The following formula represents this dependency:

$$\Delta T = \frac{60}{\text{rpm} \cdot \text{order resolution}}$$

The formula shows that in this calculation method, the time window width (Fourier analysis block length) depends on the rpm. The window width decreases with increasing rpm values. Furthermore, the window width is inversely proportional to order resolution. This means, the finer the selected resolution, the longer the analysis time window gets. At a resolution of 0.1, each time window ΔT covers 10 revolutions, whereas at an order resolution of 0.5 it is only 2 revolutions. Similar to an FFT analysis, which is subject to an effect called frequency-time uncertainty, a higher time resolution leads to a lower order resolution and vice versa. Figure 4 shows the difference between an order analysis with an order resolution of 0.01 and one with a resolution of 0.2. All other parameters have been kept identical.

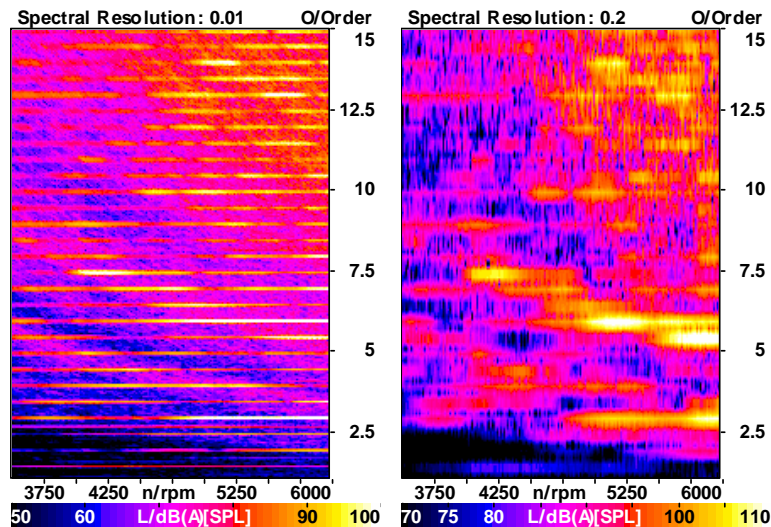


Figure 4: Comparison of different order resolutions; left diagram: order resolution 0.01
right diagram: order resolution 0.2

Moreover, it is possible to integrate the power of DFT lines in broader bands. The following settings are available:

- "off": With this option the DFT lines will not be integrated.
- "Order": If the option "Order" is used, the width in orders can be specified in the field "width". The DFT lines are integrated according to this width, which is symmetrically split around the nodes. Thus, high resolution and reasonable bandwidth can be combined in order to e.g. determine the levels of fractional orders with an appropriate width.
- "Hz": With this option the integration is done with a fixed bandwidth, which is specified in "Hz" in the field "width". The higher the speed of rotation is, the narrower the width (measured in order) gets.
- "* Frequenz": With this option the bandwidth of integration is defined by a factor. Seen on a logarithmic frequency scale, the integration bandwidth is symmetrically around the respective order, e.g. "0.707" ($= \sqrt{2}/2$) = octave width) can be a reasonable factor.
- "Bark": The option „Bark" effects that the DFT lines are integrated in critical bandwidths according to the value entered in the field "width".

If the selected width is lower than the selected spectral resolution, the value of the spectral resolution defines the analysis. (This corresponds to the option "Off").

For the analysis window used for the DFT, several parameters can be specified in the *Properties* dialog. These include the desired window function, e.g. Rectangle, Hanning, Hamming or Kaiser-Bessel, and parameters for time weighting and spectral weighting. The *Time Weighting* setting specifies the integration time period, over which the level curves are to be averaged. Depending on the selected integration time, this leads to more or less smoothing of the level curve. The *Spectral Weighting* setting allows the level curve to be displayed with A-, B-, C- or D-weighting. The difference between an A-weighted and an unweighted order analysis is shown in figure 5.

By using A-weighting the level is reduced at high and low frequencies. Due to the selection of the displayed axis range the decay at low frequencies can be seen particularly well in figure 5.

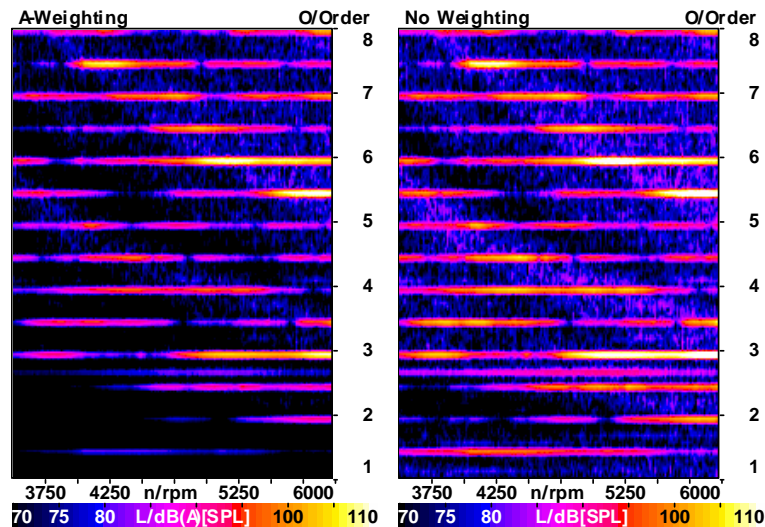


Figure 5: Comparison of an A-weighted order analysis (left diagram) and an unweighted order analysis (right diagram)

In the *Slope* select box, the direction of the rpm change can be specified, e.g. *Rising* for an engine run-up. The numbers specified under *Spectral Range* define the analysis range, i.e. the minimum and maximum order to be analyzed. Furthermore, the *Phase* select box provides a choice whether the result should include complex data. If *off* is selected, only the *level* of the orders is calculated and displayed. The *Reference Channel* setting calculates a complex order spectrum based on the selected reference channel. In the *Representation* tab of the *Properties* dialog, the display method for the complex results can be selected (e.g. *Amplitude/Degree*). By a click on the second tab (“Representation”) the display of the complex results can be selected (e.g. “Amplitude / Degree”).

As described above, an order analysis requires rpm information. This information can either be stored in a digital pulse channel or in an additional, analog channel. In the *Properties* dialog of the sound file the channel containing the rpm information can be selected (figure 6). If no rpm information was recorded with the sound file, it can be reconstructed later from a known significant order using the *Pulse Wizard*.

The Application Note „Using Different Reference Quantities in ArtemiS” describes in detail the selection of reference quantities and several particularities (e.g. using different quantities for calculating and displaying).¹

¹ This Application Note can be downloaded from the DownloadCenter on our web site (www.head-acoustics.com).

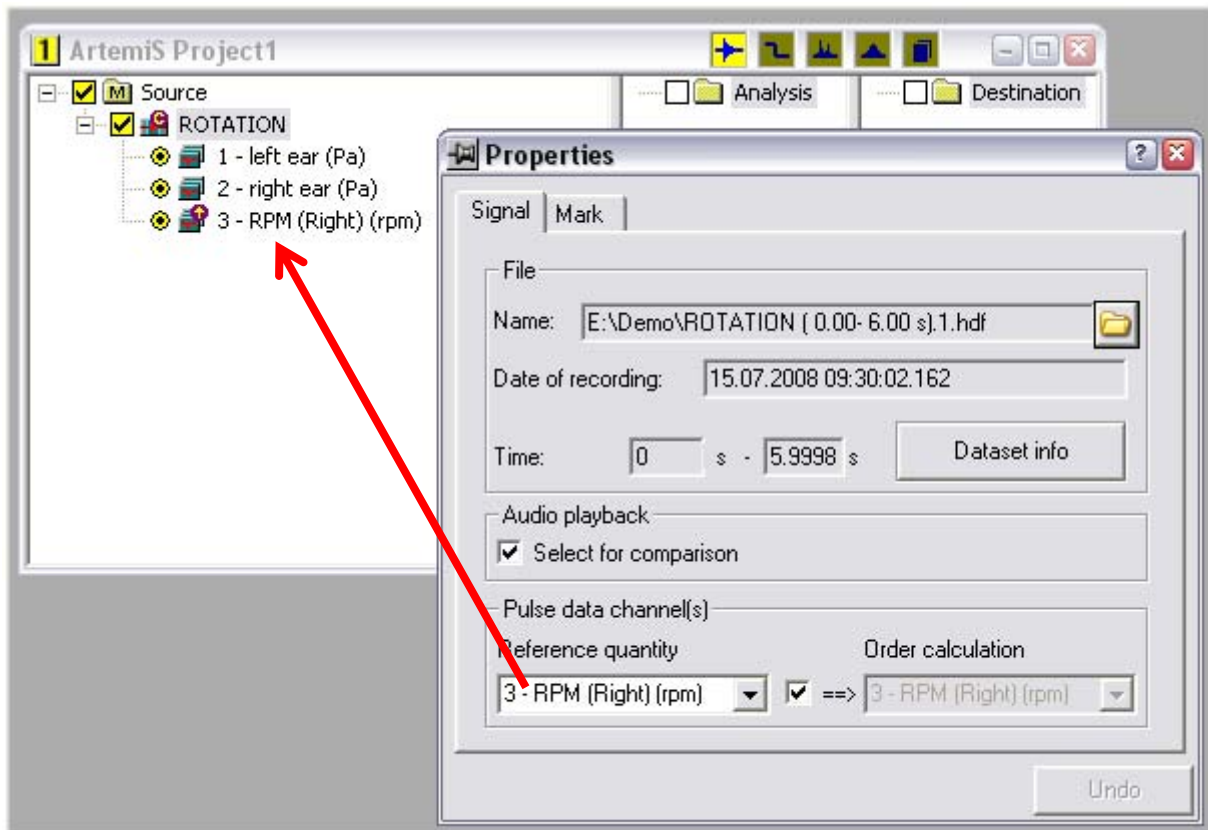


Figure 6: Separate rpm channel

Figure 7 schematically shows the calculation procedure of an order analysis vs. rpm: First the DFT calculations are performed at the pre-set revolution speed values with the rpm-dependent window widths ΔT . In this example, the revolution speed increases, i.e. the width of the analysis window gets smaller with each step. The analysis results of all the rpm sampling points are finally displayed in a three-dimensional diagram. Below this composite spectrum, the figure shows another spectrum where the sound level is represented by color. The x-axis of this diagram represents rpm and the y-axis represents the orders.

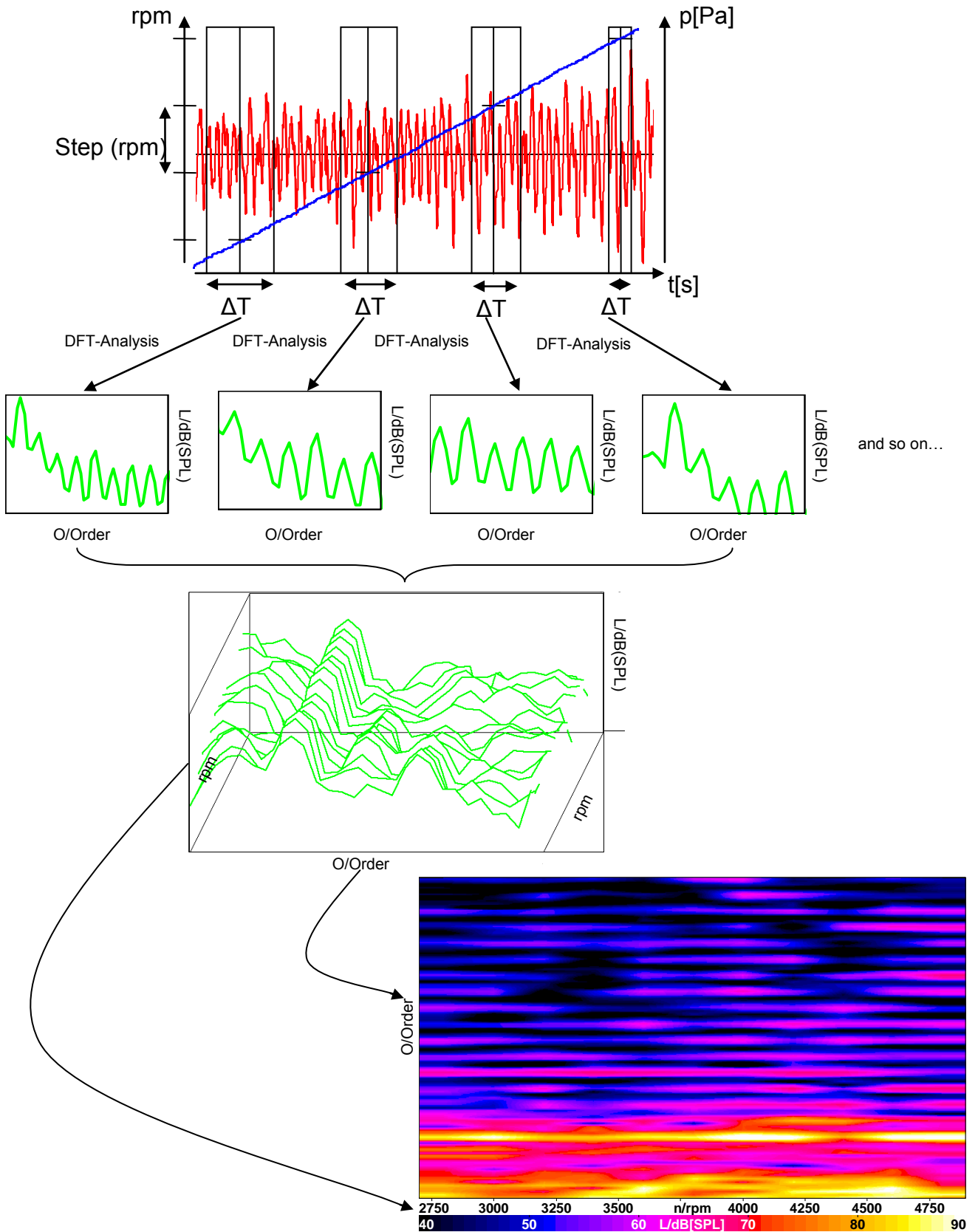


Figure 7: Scheme of an order analysis process

To get a display of the level curve of one or several individual orders separately, ArtemiS provides the *Cut* function. This function can be enabled or disabled on the second tab of the *Properties* dialog (*Representation*). The default setting cuts the 2nd, 4th and 6th order from the spectrum. The resulting cuts then show the level curve of the respective order versus rpm in a 2D diagram.

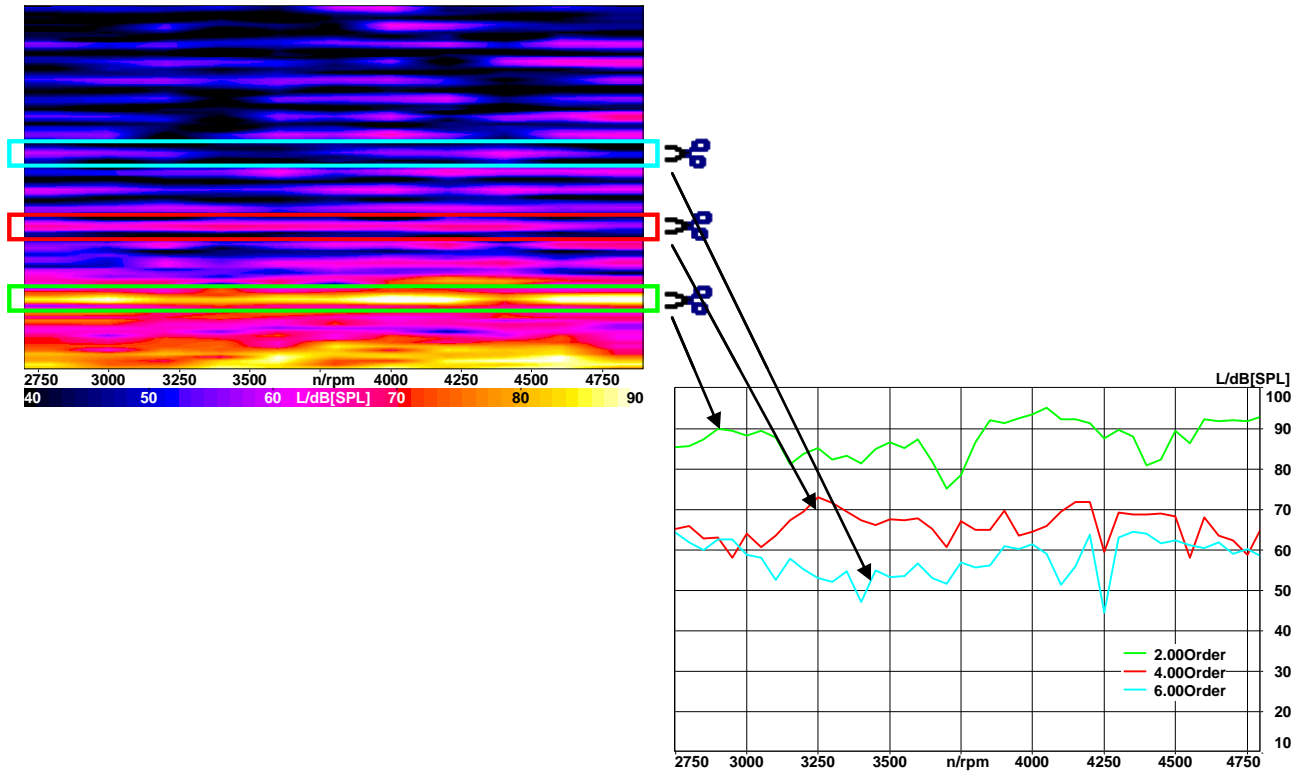


Figure 8: Order cut from a spectrogram

In addition, the analysis shown in the example above can also be represented versus time. To achieve this, the analysis is performed in a similar way as described above, but the results of the order analysis are not plotted over an rpm axis, but over a time axis. For this reason, the step width is not specified in rpm as in the analysis vs. rpm, but in seconds.

Furthermore, it is also possible to calculate and display the mean sound level for each order averaged over time or rpm. For this purpose, the analysis is performed as described before; but the sound level displayed is the average for all sampling points of an individual order. For clarification, a cascade representation of the order analysis (see figure 9) has been chosen here rather than a spectral diagram. In the *Properties* dialog, the user can select whether a diagram versus time or a diagram versus rpm should be used as the basis for averaging. Depending on this choice, the distance between the individual analysis points is given either in rpm or in milliseconds. For a nearly steady RPM situation, averaging versus time may be more useful.

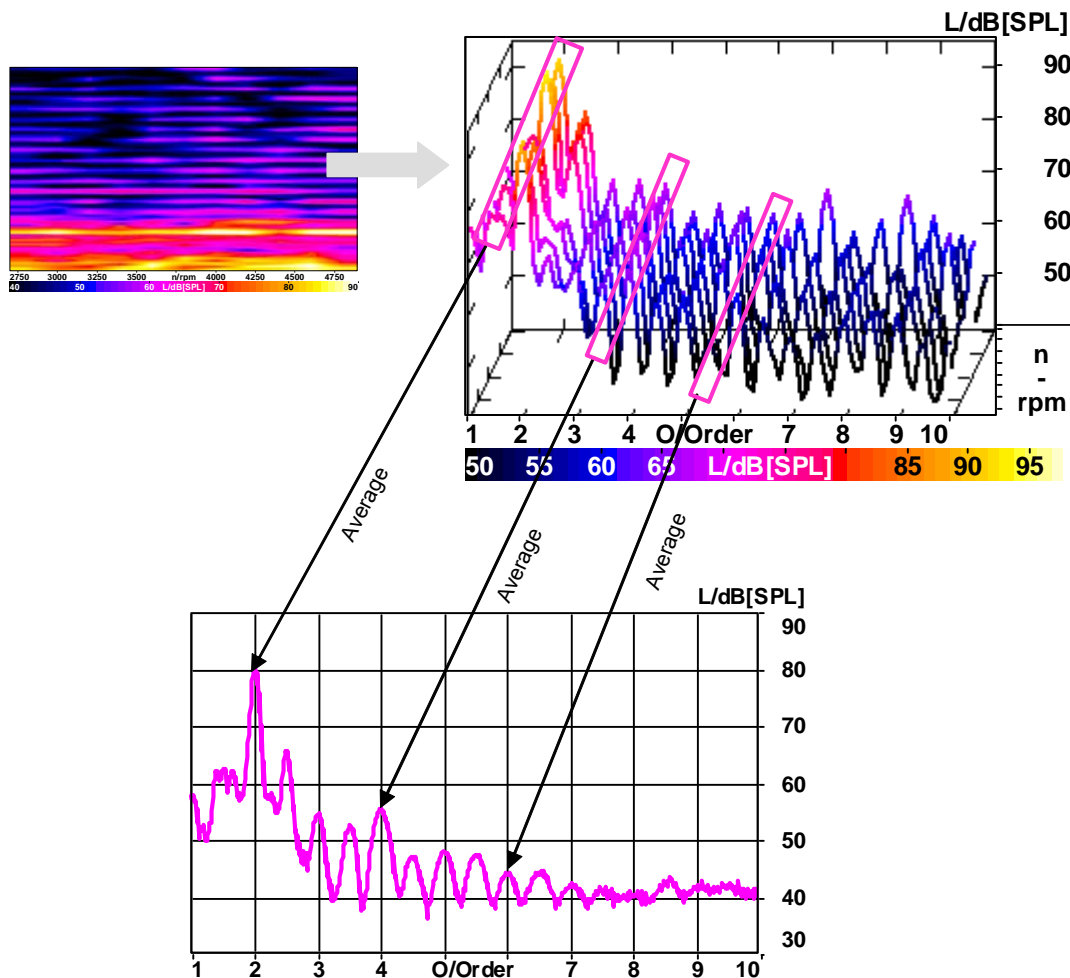


Figure 9: Averaged order analysis

Calculating an Order Spectrum with the “RPM-Synchronous Resampling” Method

The *Variable DFT Length* algorithm presented above is suitable for recordings where the rotational speed does not change too quickly. When an order analysis is performed on data where the rotational speed changes very rapidly, the frequency of an order does not remain constant within the time window ΔT . Thus rapid changes in the rotational speed lead to a “smearing” of the order resolution when the *Variable DFT Length* method is used. To avoid this smearing effect, a different calculation method called *RPM-synchronous Resampling* can be selected.

In this method, the signal is no longer sampled in equidistant time intervals, but in equidistant rotation angle intervals (“resampling” of the signal). A Fourier transformation of a signal with a conventional, time-based sampling rate results in a frequency spectrum, which can be converted into an order spectrum if the rpm values are known. In contrast, the Fourier transformation of a signal sampled synchronously with the revolution speed results directly in an order spectrum. The rpm-synchronous signal sampling makes sure that the analysis window contains the same number of signal samples at each sampling point. That means that at higher revolution speeds the signal is sampled faster accordingly, so the frequencies within the analysis window are not smeared.

The sampling intervals and the DFT window width are automatically adjusted so that the desired order range and the desired order resolution are achieved.

The rpm-synchronous sampling method is especially well suited for the following cases:

- Recordings with rapid rpm changes
- High resolution of orders
- Analysis of high orders

Since the level calculations of high orders in this method require very high sampling rates, the necessary computing time increases significantly if a large order range (*Spectral Range*) is selected. To reduce the processing time, the analysis should therefore be limited to the order range of interest.

Figure 10 shows the difference between the two calculation methods. The diagrams on the left show the results achieved with the *Variable DFT Size* method, whereas the diagrams on the right show the results using *RPM-synchronous Resampling*. For the two upper diagrams, an order resolution of 1/10 was selected, for the two lower diagrams an order resolution of 1/50 was used. At the lower resolution (1/10 order), hardly any difference is recognizable between the two methods. However, the difference can easily be seen if a higher resolution (1/50 order) is chosen. In this case, the *RPM-synchronous Resampling* method makes the individual orders appear much clearer and sharper.

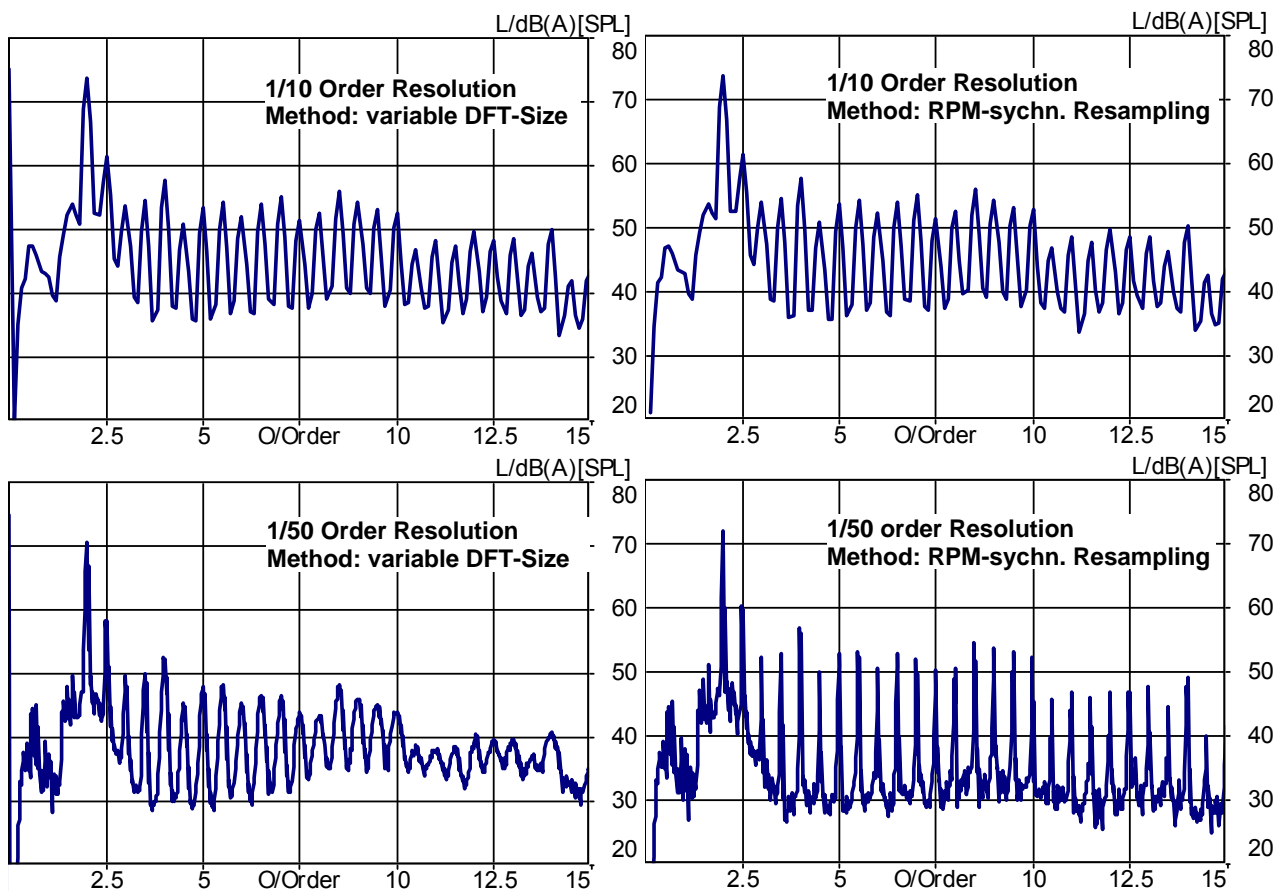


Figure 10: Comparison of the two calculation methods *Variable DFT Size* and *RPM-synchron. Resampling*

Choosing the best Settings

For the proper calculation of an order analysis, it is important to choose the appropriate settings in the *Properties* dialog. However, there are no general rules which settings work best for an analysis. They must be selected according to the specific requirements for the desired analysis results (e.g. good time resolution or good order resolution). Furthermore, the increased computing time requirements of *RPM-synchronous Resampling* method must be considered. The following table provides an overview of possible requirements and the corresponding recommended settings:

Requirement	Settings
High time resolution	<ul style="list-style-type: none"> • Low order resolution (<i>Spectral Resolution</i>) • Small sampling intervals (<i>Step</i>)
High order resolution	<ul style="list-style-type: none"> • High order resolution (<i>Spectral Resolution</i>) • <i>RPM-synch. Resampling</i> method for recordings with rapid rpm changes
Low computing time	<ul style="list-style-type: none"> • <i>Variable DFT Size</i> method • Small order range (<i>Spectral Range</i>)
Smoothed curves	<ul style="list-style-type: none"> • Setting <i>Fast (Time weighting)</i>

Table 1: Analysis requirements and corresponding recommended settings

Note

In order to use the features presented in this application note you will need the ArtemiS Basic version (Code 4600) and the ArtemiS Signature Analysis Module, ATP 03 (Code 4603).

Do you have any questions or remarks? Please write to: imke.hauswirth@head-acoustics.de. We look forward to receiving your response!