Frequency analysis put into practice

Technically, guitar strings, audio amplifiers, filters or rotating shafts are one and the same, namely signal sources. These contain substantial information. The content is decoded during the oscilloscopic analysis and the interpretation of the time signals. It facilitates the development, optimization and quality evaluation for mechanical and electrical components. The Fast Fourier Transformation (FFT) acts as an important tool in this process. The following issues will subsequently be inspected: What significance does this method have for continuous and non-continuous time signals; what are its potential uses; and which error sources need to be considered?

Frequency analysis via FFT is all about breaking down a time signal into its individual frequencies. If the signal is periodic, the analysis provides a complete frequency spectrum, as long as a minimum of one period has been completely captured. In theory, non-periodic oscillations must also be captured completely to guarantee clear results. However, in practice this is not possible. That is why many manufacturers of modern oscilloscopes offer helpful features to support the analysis.

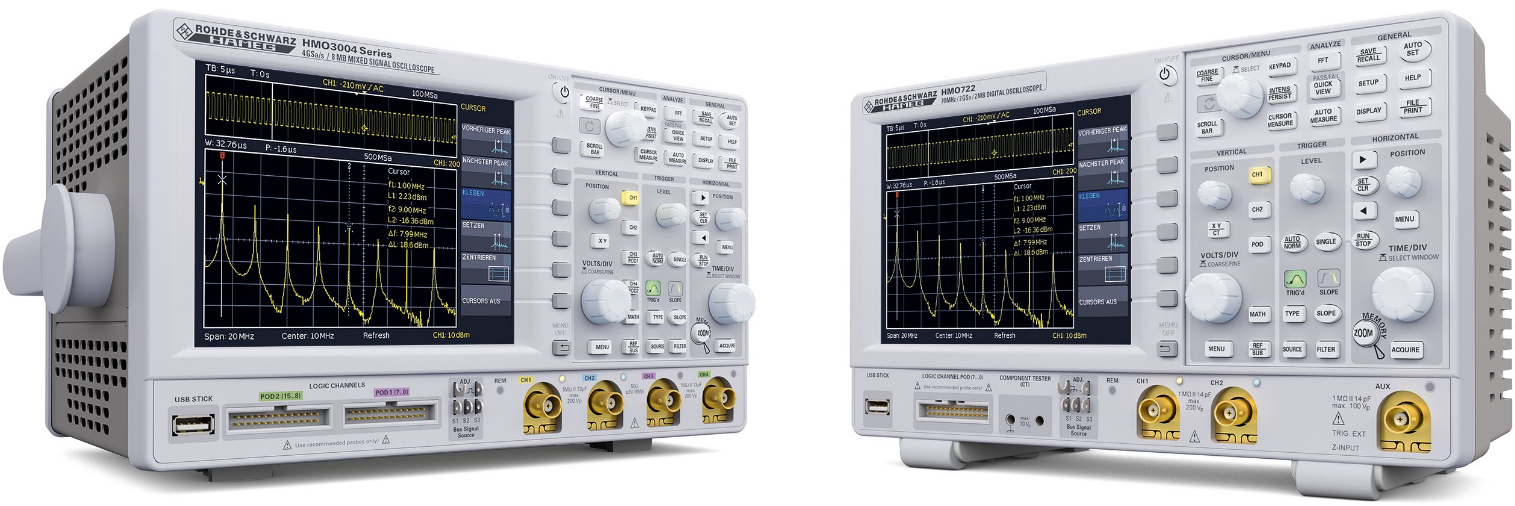
From the Automobile to Wobbling

Electrical engineering is not the only field in which the frequency analysis is relevant: It is also used in the automotive industry, energy supply or mechanical and plant engineering to optimize rotating components or to check the degree of wear. In electrical engineering, wobbling filters to determine transfer functions or assessing the distortion of audio amplifiers are typical cases. Since filter wobbling can typically be measured with the XY function of oscilloscopes, this example will not be discussed in further detail. Nevertheless, the FFT function offers an alternative solution to this in the low frequency range. It is at least equivalent, if not oftentimes superior, in terms of requirements regarding measurement accuracy and frequency stability. Many traditional spectrum analyzers are even unable to provide similar results as they cannot reach the low frequencies range. The Hameg Instruments measurement instrument (HMO3000 series) that will subsequently be used in all screenshots is an exception: By activating the envelope curve, it can be configured to pass the entire frequency analysis in a single step.

Case Study 1: Periodic Signal

Due to the non-linear characteristic curves of their components, even high-quality audio amplifiers end up distorting incoming signals. The distortion factor serves as a parameter to quantify this distortion. Nowadays, digital measuring bridges are often used to determine the distortion factor. These measuring bridges consist of a signal generator to generate fundamental oscillation, a device under test (DUT) and a FFT analyzer. Modern oscilloscopes have a clear competitive advantage: They cover a noticeably broader frequency band and allow tests well into the megahertz range. This ensures that distortion factor definitions are not only limited to the audio range. It is also possible to test other signal amplifiers. Regardless of the instrument used, frequency spectrums obtained eventually show the RMS values of individual harmonics and of the distortion factor.

Oftentimes, the distortion of input signals cannot be detected with the naked eye. For instance, the sine wave signal displayed



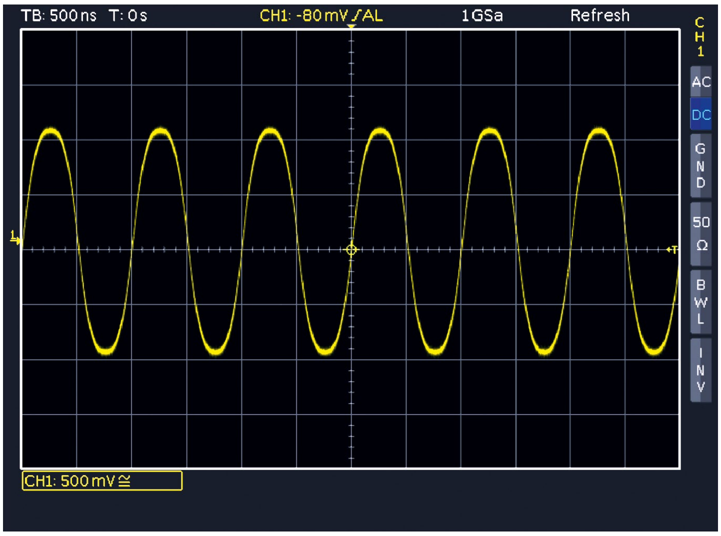


Figure 1: A sinusoid signal with 1 MHz and 1 V amplitude that at first sight appears undistorted

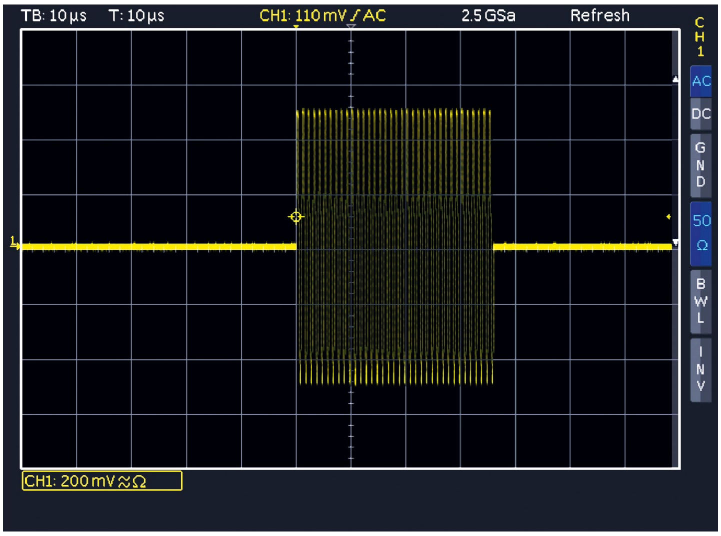


Figure 3: Example of a non-periodic time signal (f = 1 MHz and 36 cycles)

in figure 1, with a frequency of 1 MHz and an amplitude of 1 V, appears to be undistorted. Only the frequency spectrum (figure 2) clearly displays additional harmonics that occur as harmonic oscillations for multiples of the basic frequency. The additional harmonics with a decreasing level at 2, 3 and 4 MHz follow after the main signal with a frequency of 1 MHz.

Case Study 2: Non-Continuous Signals

What happens if there is no periodic input signal? Most instruments offer the option to trigger the spectrum at just the right moment to then check it in 'STOP' mode at a later time. However, at that point, many oscilloscopes with FFT functionality calculate the spectrum only once and store the result in the memory. The base time signal will no longer be used for the calculation. Consequently, an investigation of all parts of the signal will no longer be possible.

Oscilloscopes of the HAMEG HMO series work differently: Since FFT is also active for previously stored signals, it is possible to subsequently analyze any sections of those signals captured in single shot mode or stop mode with an adjustable window width. Figure 3 features such a non-periodic signal.

For the analysis, it is advisable to first place the measurement window (upper screen area) outside the sine burst (Fig. 4).

The spectrum (lower screen area) displays the noise floor since no signal portions are positioned within the measurement window. If the measurement window is now shifted to the right so that it covers the sine completely, the cursor indicates a frequency of exactly 1 MHz (Fig. 5). The spectral line protrudes visibly from the spectrum without displaying additional lines.

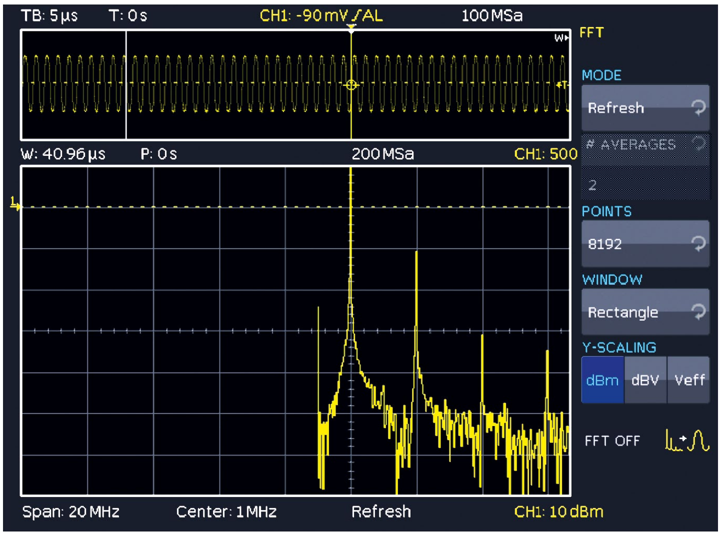


Figure 2: The frequency spectrum exposes the signal distortion

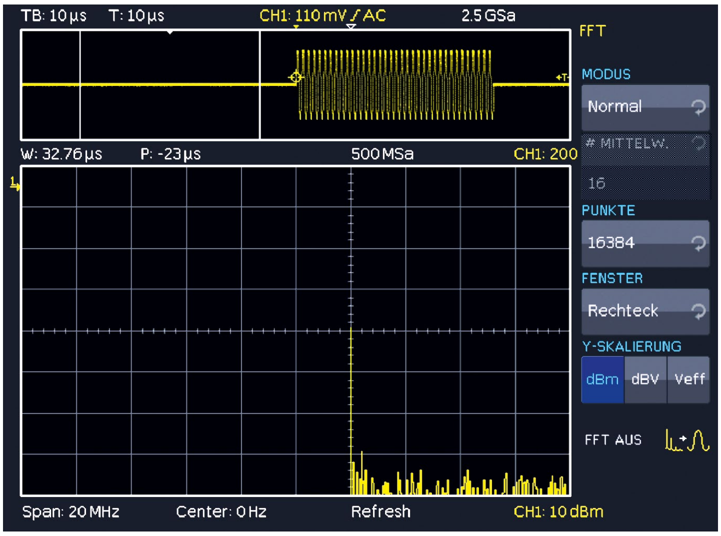


Figure 4: Measurement window (2 white vertical lines in the upper screen area) outside the sine burst

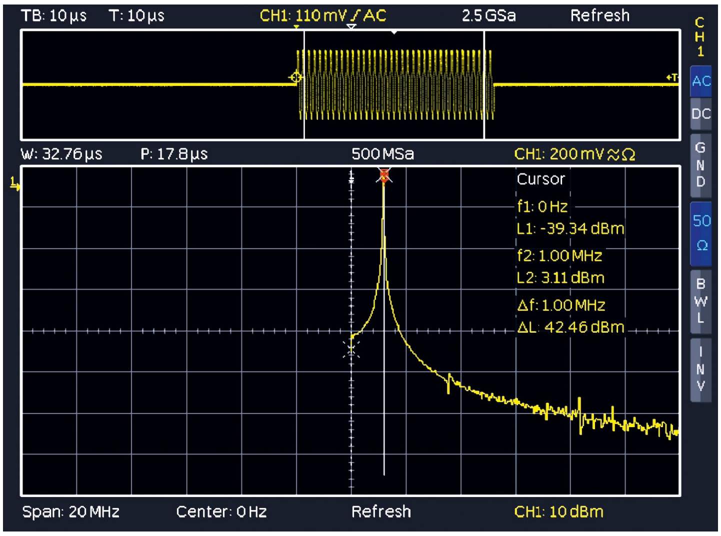


Figure 5: Measurement window covers the sine burst completely

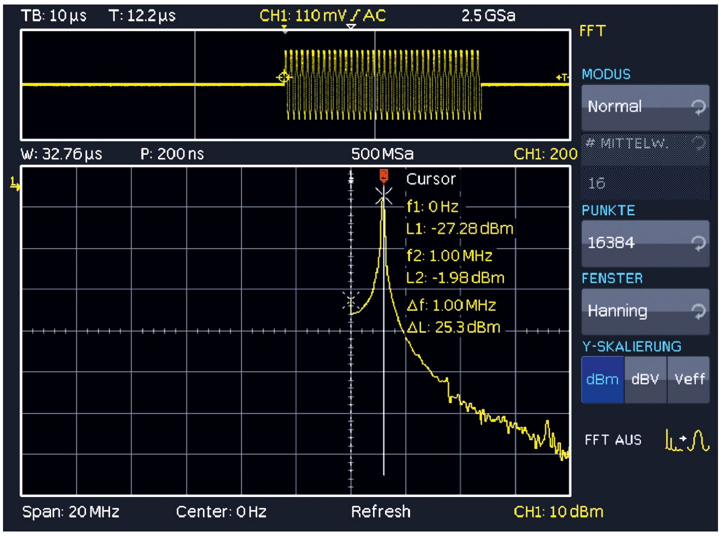


Figure 7: Spectrum with Hanning windowing instead of rectangular window

If the measurement window is shifted so that the zero line is positioned in one half and some sine cycles are positioned in the other half of the window, it will yield the following spectrum (Fig. 6).

Side lobes appear to the right and the left of the 1 MHz spectral line as a result of the hard limit impact between zero line and sine cycles. For all shown steps, the time signal is stored in the memory (STOP mode activated) while the FFT continuously recalculates the spectrum depending on the selected window. This particular feature allows the user to analyze the chronological progression of the spectrum virtually online.

The final screenshot is to serve as the basis for another experiment: How do multiple windows affect a frequency spectrum? For all previous examples, a rectangular window was used. Although this window type captures frequencies at a high degree of accuracy, it is also accompanied by more noise. A better way to suppress this disturbing interference is the use of the Hanning window, for instance. Its positive impact on the spectrum is immediately visible (fig. 7).

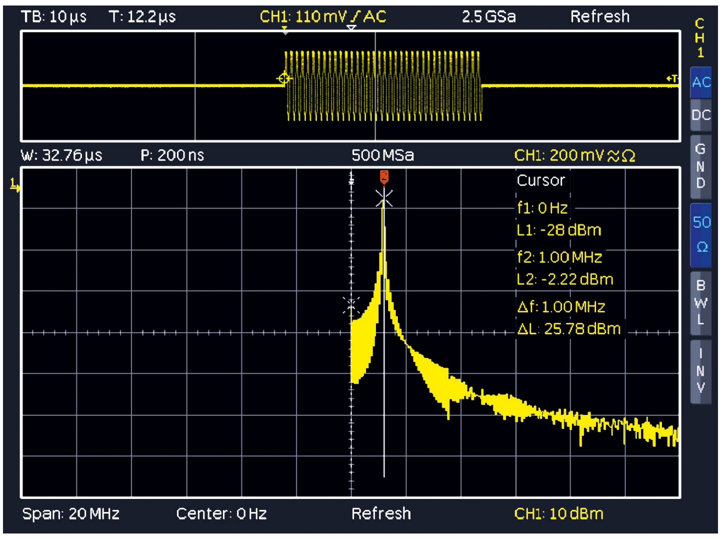


Figure 6: Measurement window only 50 % above the sine burst

The example shows the advantage of the online calculation for all FFT function in STOP mode: All operations can be applied to a single recorded signal which is available unlimitedly in the sample memory.

Smearing

Apart from its strengths, the FFT limitations that occur in practice must also be considered. This includes the so called smearing. This effect is directly related to the measurement process and causes a 'smearing' of the frequency spectrum. This is due mainly to the time signal windowing: The choice of window width and sampling rate determines the number of measurement points. This clips the time signal which, mathematically speaking, corresponds to multiplying the time signal with the window. Typically, it is not possible to capture fully completed sine waves during this trimming, causing small signals on the spectrum margins.

Since the FFT is always only applied to a section of the time signal it is impossible to fully avoid this smearing effect. However, this may be remedied by using various windows.

Leakage

A second source of error is the so called leakage effect which is also related to the windowing. If the duration of the selected measurement window does not correspond to an integer multiple of the signal period, new spectral lines occur. In reality, the sine waves of these spectral lines are non-existent. Since the spectrum is 'leaking', it is impossible to make a reliable statement about the actual spectral components of the signal. It is fairly simple, however, to minimize this effect by maximizing the selected window.

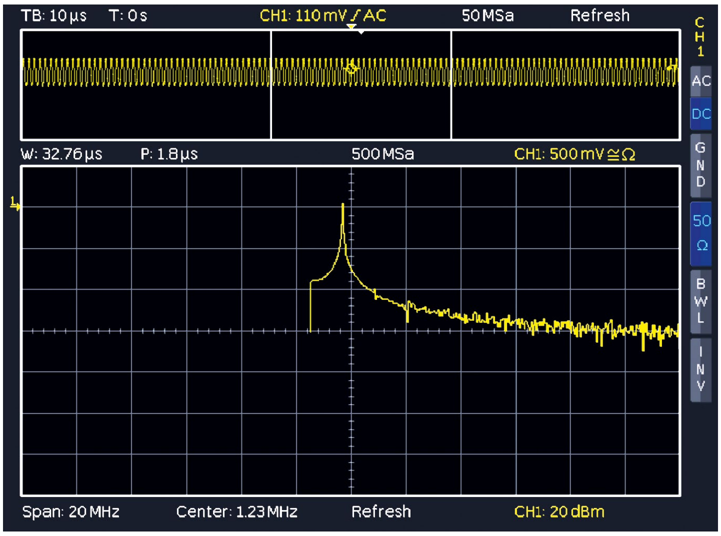


Figure 8: Time signal and frequency analysis with rectangular window. Sampling rate: 500 MSa/s

Conclusion

The FFT offers numerous options to quickly and safely analyze time signals. Put into practice, however, a few factors should be considered: For instance, if the used oscilloscope limits the number of points to a few powers of 2, the measurement options are significantly restricted. The Hameg Instruments model (HMO series) provides excellent options for FFT analysis with 65,536 points and also includes comprehensive options for cursor measurements. Additionally, it also simplifies the spectrum measurement to display the time signal, the measurement window, the analysis area of the FFT and the result all on to one screen . The option to apply multiple windows to a single signal is significant. Varying the position of the measurement window in the time signal allows a further reduction of noise components. Furthermore, potential error sources, such as leakage or smearing, can be largely eliminated.

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BASICS:

Typically, time signals consist of various sinusoidal waves (harmonics). The waves' frequencies and amplitudes characterize the signal. The Fourier transform breaks this time signal down to its frequency spectrum so that the harmonics are displayed. From a mathematically point of view, this is carried out by applying the following formula:

$$X(f) = \int_{-\infty}^{+\infty} x(t) e^{-j2\pi f t} \, dt$$

Periodic signals evolve into Fourier spectrums with discrete lines. In the simplest case, i.e. a sine wave with the same amplitude and frequency, is illustrated as a line in the frequency spectrum (fig. 1 and 2).

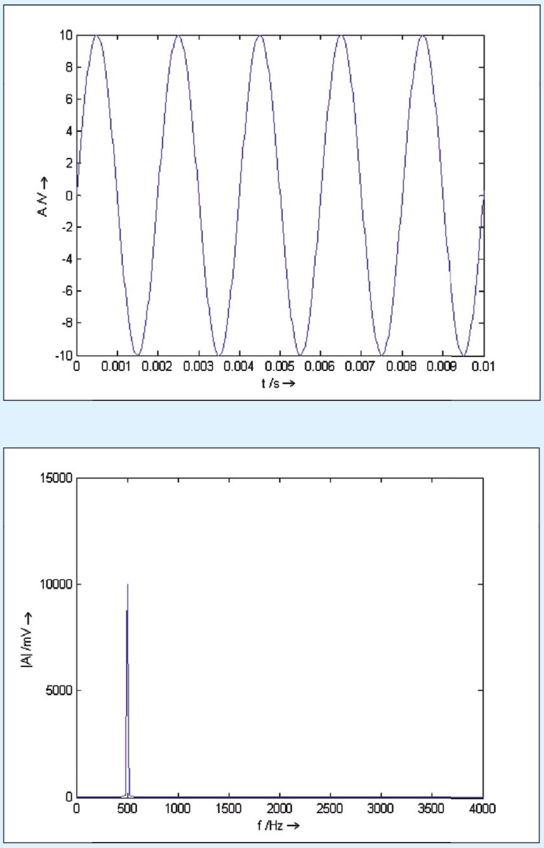

Figure 1 and 2: Time signal (10 V / 500 Hz) and frequency spectrum with discrete line where A = 10,000 mV and f = 500 Hz

Non-continuous signals are an example of the other extreme: Due to their aperiodicity, they include numerous harmonics with different amplitudes. Consequently, the Fourier spectrums are also non-continuous. Put to practice, problems may potentially arise when signals are always viewed via a defined time window. The settings for time window and sampling rate ultimately define the validity of the analysis. During the FFT, information (other than the phasing) does not get lost. This is true despite the fact that the amount of data is significantly reduced. The key to this lies in the incremental breakdown of the summation formula. From one level to the next, the amount of sample values is bisected so that the required computation drops significantly below 1 % in some cases.

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