UNIVERSITÀ DEGLI STUDI DI PADOVA

Measuring distortion in a linear amplifier

Lecture #7

Electronic measurements

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Linear Amplifier distortion

- **Linear amplifier:** electronic circuit that has an output that is proportional to the input while providing additional power to the load

- **Distortion** ⇒ Non linearities within the circuit
  - Alterations in the shape of the signal
  - Changes in its spectral components

- **Audio amplifiers** ⇒ fidelity of sound reproduction
- **Radio-frequency amplifiers** ⇒ avoid spectral interference

Total Harmonic Distortion

- **Test signal** ⇒ Pure sinusoid
  - **Harmonics**: sinewaves at some integer multiples of the original sinewave frequency
  - $V_{RMS(1)}$ RMS value of the test sinewave at the fundamental frequency
  - $V_{RMS(i)}$ RMS value of the i-th harmonic
- **Total Harmonic Distortion (THD)**

$$THD[\%] = \frac{\sqrt{\sum_i V_{RMS(i)}^2}}{V_{RMS(1)}}$$

$$THD[dB] = 20log_{10}\left(\sqrt{\sum_i V_{RMS(i)}^2}\right) - 20log_{10}(V_{RMS(1)})\ \text{[dBV]}$$

Total Harmonic Distortion

- **Intermodulation** ⇒ Pair of sinewaves as test inputs
  - Frequencies f_1 and f_2
  - Components at frequencies $f_1, f_2, 2f_1, 2f_2, f_1 \pm f_2, 2f_1 \pm f_2, f_1 \pm 2f_2$, etc…

- **Clipping** ⇒ Output saturation (output amplitude outside range)

- **Slew rate:** maximum rate of change that the amplifier output can achieve
  - Function of frequency and amplitude

Distortion in a linear amplifier

- **Oscilloscope distortion**
  - Check for distortion within the measuring instrument
- **Device bandwidth evaluation**
  - Approximately estimate the frequency band of interest
- **Measurement of amplifier harmonic distortion**
  - Determine THD
- **Analysis of intermodulation distortion**
  - Detect the presence of intermodulation effects

Oscilloscope settings

- **FFT function**
  - Frequency span (F_{span}) and the centre frequency (F_{centre})

- **Vertical axis**
  - Absolute RMS voltage values
  - dBV

$$V_x[\mathrm{dBV}] = 20 \cdot log_{10} \frac{V_x[V_{RMS}]}{1[V_{RMS}]}$$

  - **Reference level**: vertical axis middle point on the screen
  - Vertical cursors ⇒ direct reading in dBV

Oscilloscope distortion

- **The oscilloscope is not a spectrum analyzer…**

- **Distortion measurements:**
  - Detecting signal components at different frequencies from the input signal
  - Check for distortion within the measuring instrument itself
    - **Non-uniformity of the ADC quantization characteristic**
    - **Non-linearity in the input channel**

- Generator output connected directly to the DSO input
- Test frequency in the **same range** used for amplifier testing

Spurious-free dynamic range

Oscilloscope distortion

- **Instrument settings:**
  - Center frequency: $\cong 5 \cdot f_{Test}$
  - Frequency span: $\cong 10 \cdot f_{Test}$
  - vertical scale factor: 10 dB/div

- **Noise floor**:
  - Signal quantization
  - Electrical noise introduced by the input channel stages

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Random process whose variance σ_{DSO}^2 is the sum of the variances of the two independent components

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High resolution mode

Device bandwidth evaluation

- **Measurement steps:**
  - Power up the amplifier and select, a **sinusoidal waveform** from the signal generator
  - Send the signal **in parallel** to the amplifier and to one of the oscilloscope inputs
  - Connect the **amplifier output** to another of the oscilloscope inputs
  - Adjust the amplitude of the input signal to avoid any distortion at the output
  - Determine the reference points:
    - At the **centre frequency** the amplifier gain is maximum, and the output sinewave is in opposition to the input
    - At the **-3 dB cut-off frequencies**, both lower and upper, the output sinewave amplitude is approximately 30% smaller than at the centre frequency

Measurement of amplifier harmonic distortion

- **Measurement of THD:** Analysis of the amplifier output to measure the RMS values of the fundamental and harmonic components

- Reading of V_{RMS} ⇒ Positioning a vertical cursor on the corresponding spectral peak top

- RMS V conversion ⇒ $V_{RMS}[V] = 10^{\frac{V_{RMS}[dBV]}{20}}$

- Use of a spectral window with low value of **Scalloping Loss**

Fourier analysis

- DFT-based sinewave spectrum

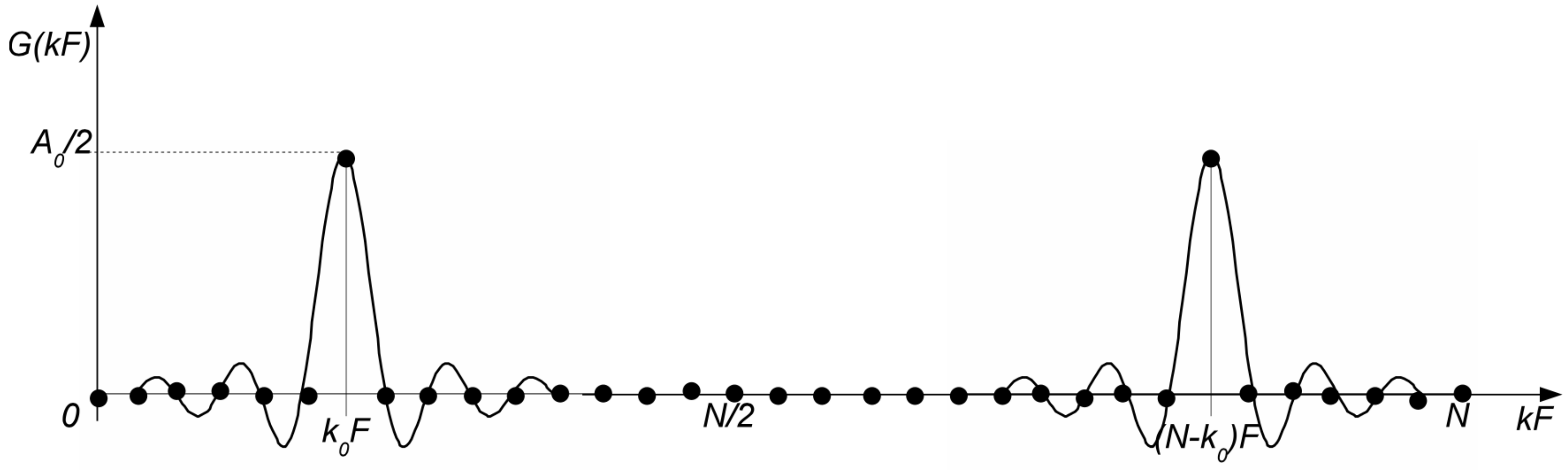
$$x(nT_s) = A_0 sin(2\pi f_0 nT_s + \phi_0), n_0 \leq n \leq n_0 + N - 1$$

$$X_{DFT}(kF) = \frac{A}{2j} e^{j\phi_0} \cdot \frac{\widetilde{W}_R(kF - f_0)}{NT_S} - \frac{A}{2j} e^{-j\phi_0} \cdot \frac{\widetilde{W}_R(kF + f_0)}{NT_S}$$

Fourier analysis

- When the observation interval $T_W = NT_S$ corresponds exactly to an integer number of sinewave periods, there is one index $k = k_0$ for which:

$$NT_s = k_0 \cdot \frac{1}{f_0} \quad \text{that means} \quad f_0 = \frac{k_0}{NT_S} = k_0 F$$

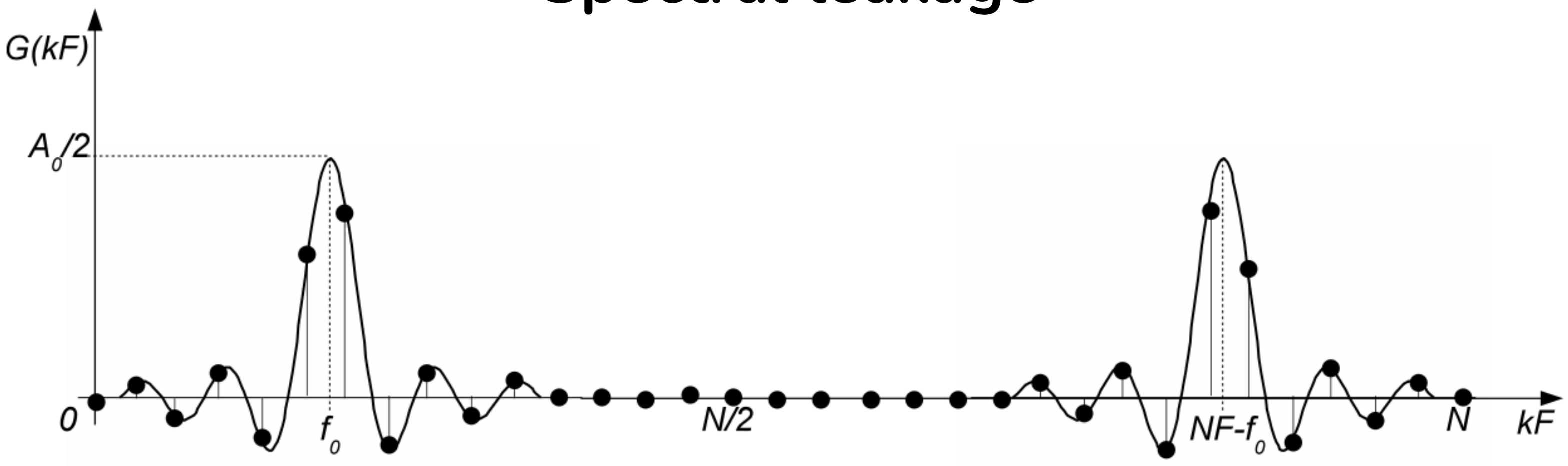


Spectral leakage

- In general, frequency f_0 is not an integer multiple of the frequency step F, therefore no index k meets the previous condition. However, there will be one index k_0 that yields k_0F as the closest estimate of frequency f_0

$$\delta = \frac{f_0 - k_0 F}{F}, \quad \text{with: } |\delta| \leq \frac{1}{2}$$

Spectral leakage



Scalloping Loss

- When a sinusoid is measured and the spectrum trace is displayed on an oscilloscope screen, the frequency can be determined by positioning a horizontal cursor to coincide with the spectral peak

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- Deviation of this estimate from f_0 is due to **frequency granularity** and the **minimum cursor step** along the frequency axis is $\Delta_f = F$, worst-case deviation is $\Delta_f\ /\ 2 = F\ /\ 2$

Scalloping Loss

- Placing a vertical cursor over the peak in the displayed trace will yield a direct reading of RMS amplitude

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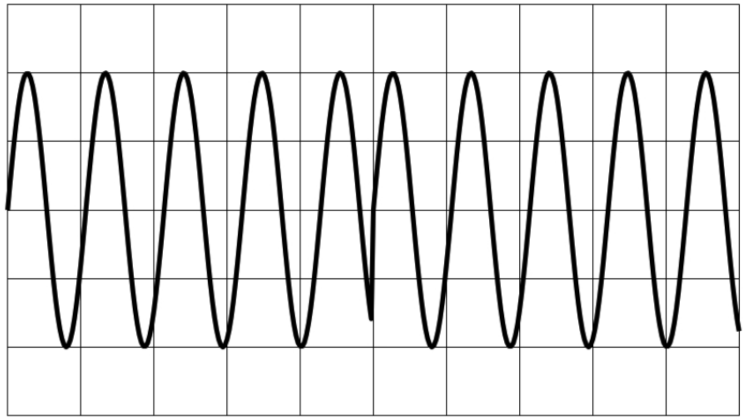
- When $\delta = 0$, the amplitude estimate is correct since $W_{R(DFT)}(0) = 1$
- For $0 < |\delta| \leq \frac{1}{2} \Rightarrow W_{R(DFT)}(\delta) < 1$, **scalloping loss**
- **Worst case scalloping loss (WCSL)** when $\delta = \frac{1}{2}$

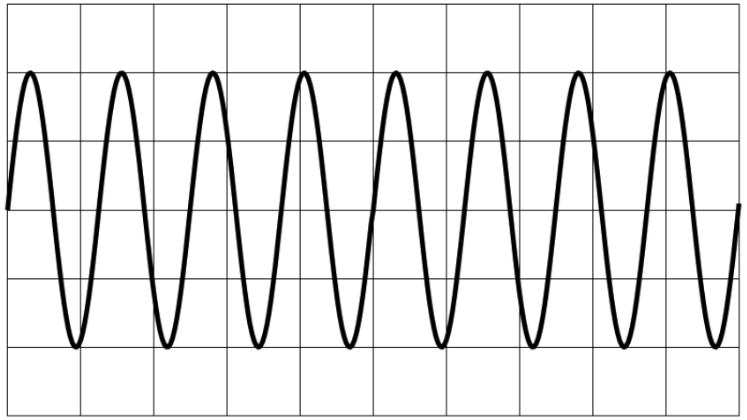
Frequency resolution

- When a signal is composed of several sinusoidal components, its DFT spectrum has multiple peaks
- If the displayed peak positions are close, interference may occur due to spectral leakage
- **Frequency resolution**: minimum separation at which two equal amplitude sinusoidal components create distinct peaks in the spectrum trace (**normalized -6 dB bandwidth**)
- With sinewaves of different amplitudes ⇒ **Masking**
  - Normalized main lobe width
  - Attenuation of the largest side lobe with respect to the main lobe
  - Side lobe fall-off with frequency

Window functions

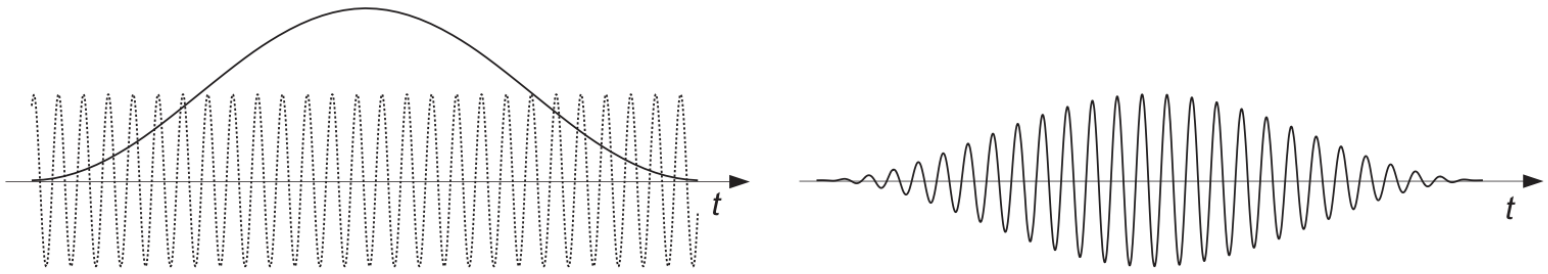


(a) $T_W \neq PT \rightarrow$ truncation



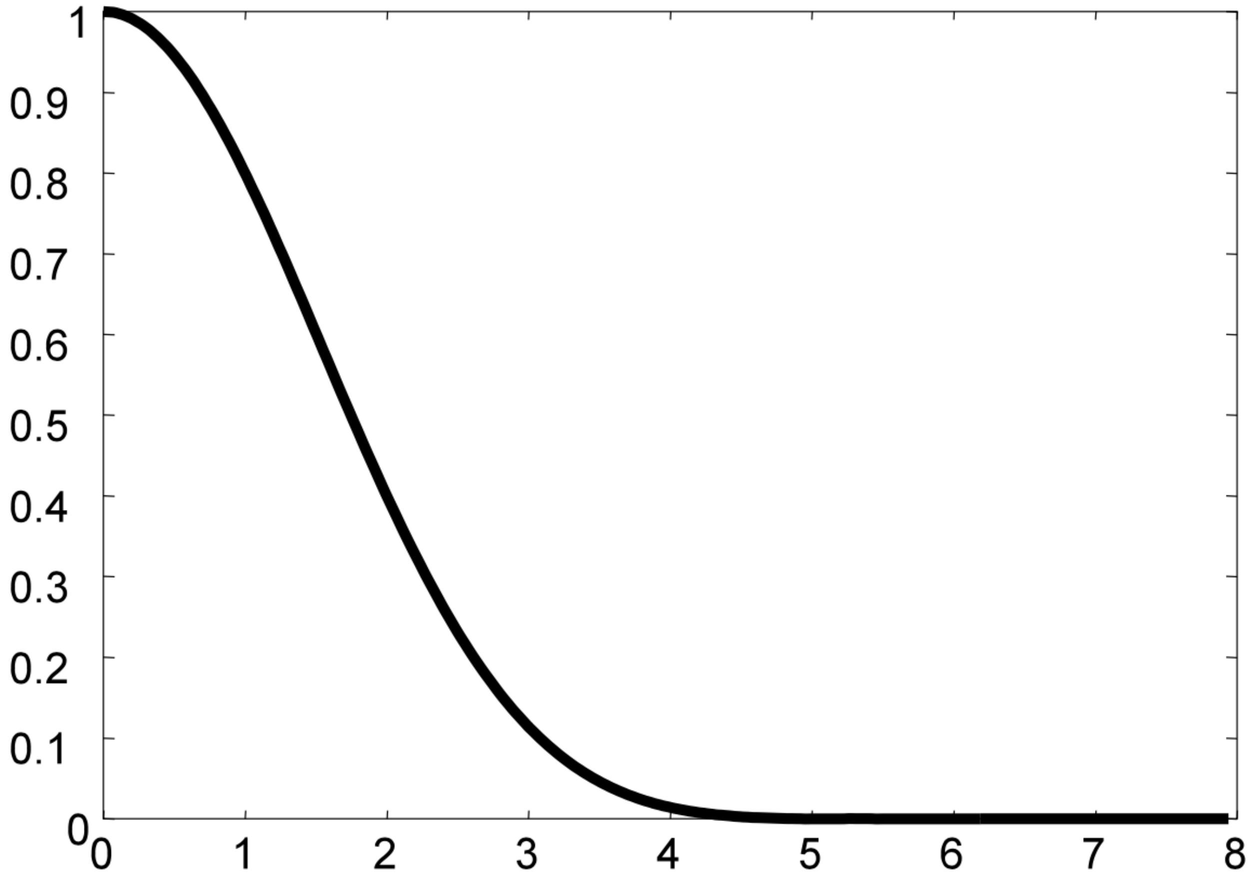
(b) $T_W = PT \rightarrow$ no leakage

Hanning Window



Window functions

Hanning Window



Windows parameters

Window	WCSL [dB]	minimum side lobe attenuation [dB]	main lobe width [bin]	$2 \cdot B_{-6dB}$ [bin]	ENBW [bin]
uniform	3.92	13	2	1.21	1
Hann (*Hanning*)	1.42	32	4	2	1.5
Blackman-Harris	1.13	71	6	2.27	1.71
flat-top	< 0.01	93	10	4.58	3.77

Measurement of amplifier harmonic distortion

- **Measurement steps**
  - Select a sinusoidal waveform shape on the signal generator. Frequency should be set to a value within the amplifier bandwidth, close to the **low-frequency cut-off**
  - Connect the generator output to the amplifier input and to one of the oscilloscope input channels
  - Connect the amplifier output to another oscilloscope input channel
  - Check that waveform amplitude does not produce distortion at the amplifier output
  - Activate the oscilloscope spectral analysis function, employing the high-resolution acquisition mode
  - Set up frequency span and centre frequency so that each sinusoidal component of the signal can be singled out

Measurement of amplifier harmonic distortion

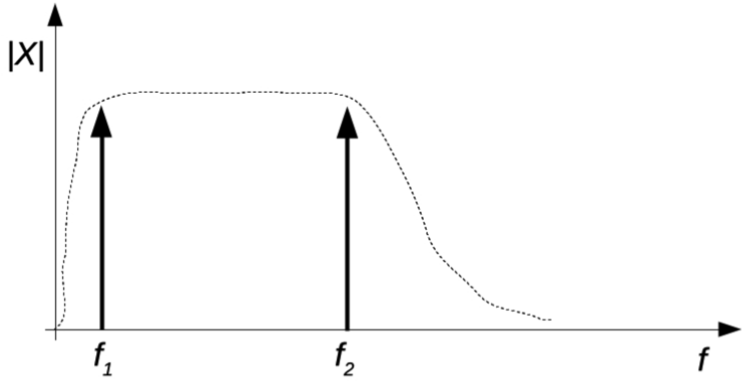
- Repeat the measurements for a **few different input signal amplitudes and frequencies**

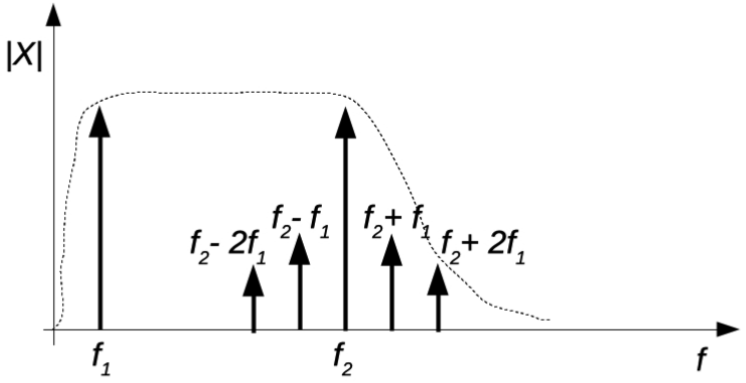
- Operations to be carried out:
  - Measure the amplitude and frequency of the **largest visible spectral component**
  - Measure the amplitude and frequency of the **most significant harmonic components**
  - Compute **THD**

Analysis of intermodulation distortion

- Sum of **two sinewaves** at different frequencies ⇒ No clipping

- First method: test signal is **the sum of a low-frequency and a high-frequency sinewave**
  - f_1 slightly greater than the low-frequency cut-off
  - f_2 slightly less than the high-frequency cut-off





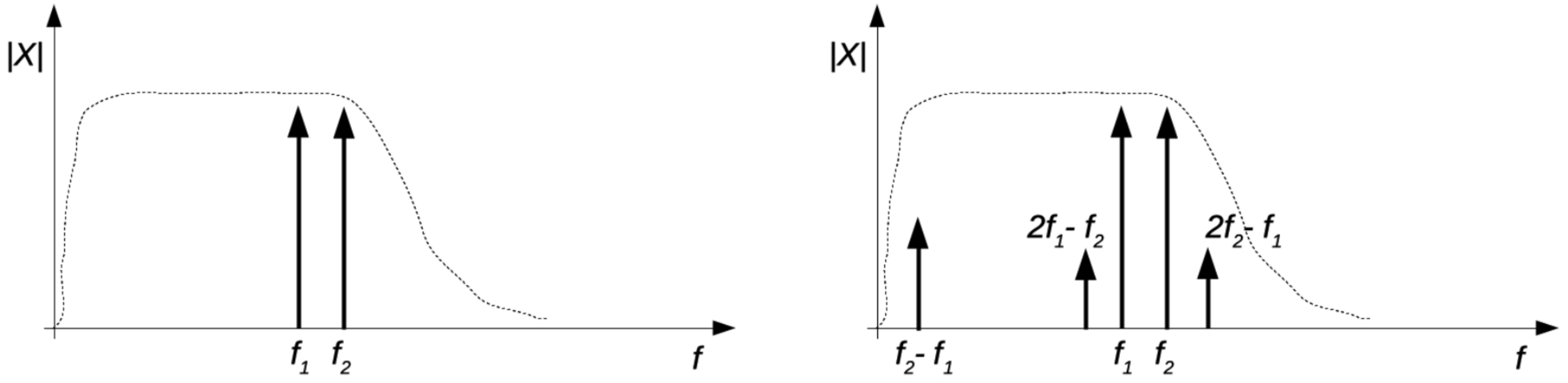
Analysis of intermodulation distortion

- **First method**: settings for the signal generator
  - Using the **Waveform** functional key, select a sinusoidal shape and input the settings for the low-frequency (f_1) component
  - From the **Modulation** menu, select the item **Type**, the modulation mode **Sum**
  - Set configuration parameters for the modulation waveform to a sinusoidal **Shape** and select the frequency (f_2) and amplitude, using respectively menu items **Sum Freq** and **Sum Ampl**
  - Activate modulation (**Modulate – On**)

- Intermodulation components can be found at frequencies: $f_2 \pm k f_1$, with k integer
- Spectral analysis setting: centre frequency f_2 with frequency span $10 \cdot f_2$

Analysis of intermodulation distortion

- **Second method**: test signal is the sum of two equal-amplitude sinewaves at two close and comparatively high frequencies
  - The largest intermodulation component will be found in this case at the low frequency $f_d = f_2 - f_1$
  - Same generator settings: f_1 and f_2 close to the high-frequency cut-off



Interharmonic distortion

- **First method**:

$$D_1 = \sqrt{\frac{V_{f_2-2f_1}^2 + V_{f_2-f_1}^2 + V_{f_2+f_1}^2 + V_{f_2+2f_1}^2 + \cdots}{V_2^2}}$$

- **Second method**:

$$D_2 = \frac{V_d}{\sqrt{V_1^2 + V_2^2}}$$

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