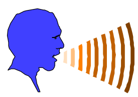
CHAPTER 7

DISTORTION



Preamble

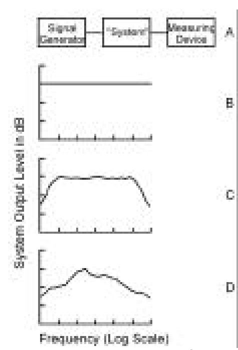
- **Deliver sound wave (or electrical signal) to a system**
- **If the system reproduces the waveform <u>faithfully</u>, the signal is <u>undistorted</u>**
- **If the shape of the waveform is <u>altered</u>, the signal is <u>distorted</u>**

Three Types of Distortion

- **Frequency**
- **Transient**
- **Amplitude**

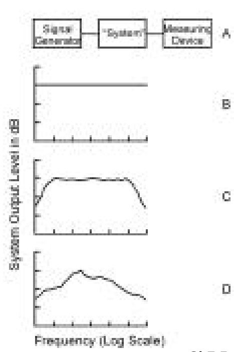
FREQUENCY DISTORTION

- **Panel A: Measurement of amplitude response of a system**
  - **The input signal must have equal amplitude for all frequencies delivered to the system**
- **Panel B: No distortion at output of system**
  - **All frequencies at output have equal amplitude, just as at input**



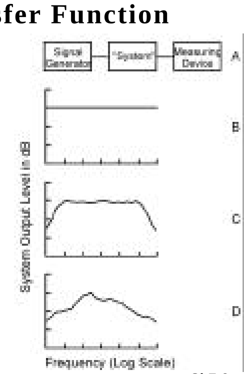
FREQUENCY DISTORTION

- **Note panels C & D**
  - **All frequencies <u>not</u> reproduced with same amplitude**
  - **System was frequency selective; filtering occurred**
  - **Signal underwent <u>frequency distortion</u>**



System Transfer Function

- **The three functions in panels B, C, & D describe the <u>system transfer function</u>, or <u>amplitude response</u>, of the system**
- **The amplitude response reveals evidence of frequency distortion**

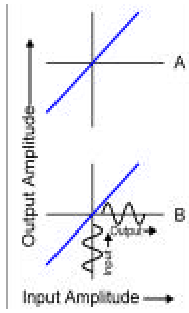


Linear Systems

- Linear systems alter only the amplitudes and phases of a signal
- They <u>do</u> produce frequency distortion
- "Frequency response" of an audio device might be described as
  - 100 Hz to 10,000 Hz
  - Flat ± X dB

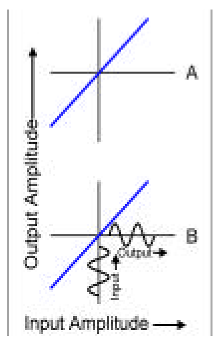
Linear Systems

- Panel A: Input-Output (I/O) function of <u>linear</u> system
  - As input amplitude increases (e.g., by 5 dB), output amplitude increases <u>proportionally</u> (5 dB)
  - Output amplitude need not <u>equal</u> input amplitude; the change is a proportional one



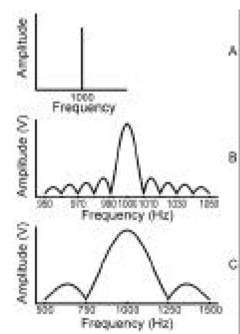
Linear Systems

- Panel B: The characteristics of the input sine wave are <u>preserved faithfully</u> in output sine wave; Why?
  - ☑ The system is linear



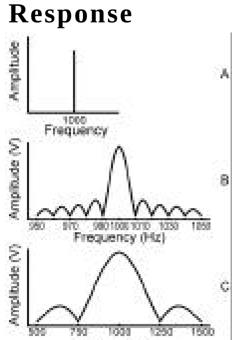
TRANSIENT DISTORTION

- The amplitude response of a sine wave is <u>not</u> really a line spectrum as shown in panel A; Why?
  - Its duration is <u>finite</u>



Effects of Duration on Amplitude Response

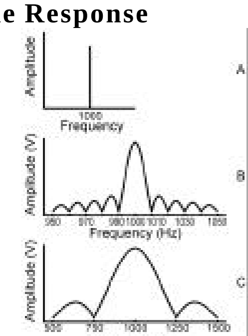
- Panel A: Infinite duration
- Panel B: 100 ms tone burst



Effects of Duration on Amplitude Response

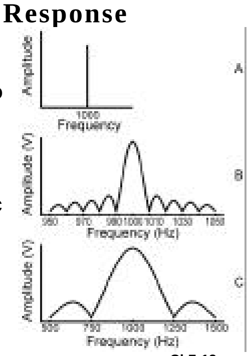
- Energy spread to surrounding frequencies, and amplitude spectrum is <u>continuous</u>
- Nulls at <u>integer multiples of reciprocal of duration</u> (100 ms)

>> 1/.1 = +/- 10 Hz
>> 2/.1 = +/- 20 Hz
>> 3/.1 = +/- 30 Hz, etc.



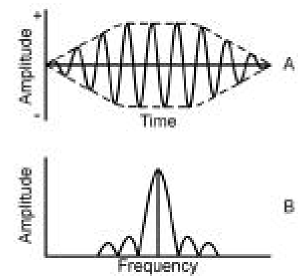
Effects of Duration on Amplitude Response

- Panel C: Duration shortened from 100 ms to 4 ms
  - 1 / .004 = + / - 250 Hz
  - 2 / .004 = + / - 500 Hz
  - 3 / .004 = + / - 750 Hz, etc
- Thus, width of each <u>lobe</u> is inversely proportional to duration



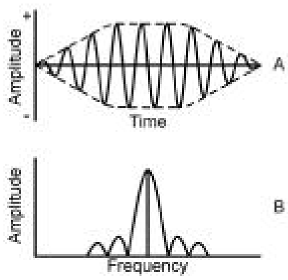
Effects of Rise-Decay Time on Amplitude Response

- Amplitude rises over time from zero to max, and falls over time from max to zero
- Panel A shows <u>amplitude envelope</u> in the time domain
- Panel B shows <u>amplitude spectrum</u> in the frequency domain



Effects of Rise -Decay Time on Amplitude Response

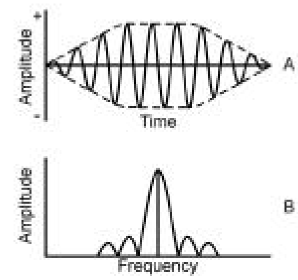
- Panel B
  - Energy spread to other frequencies: <u>Continuous spectrum</u>
  - Initiation & termination of signal produces <u>transients</u>



Effects of Rise -Decay Time on Amplitude Response

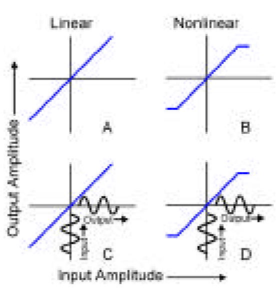
- The longer the rise-fall time, the less the transient distortion
- ANSI S3.6-1989

  >> Time from -20 dB to -1 dB shall not be less than 20 ms



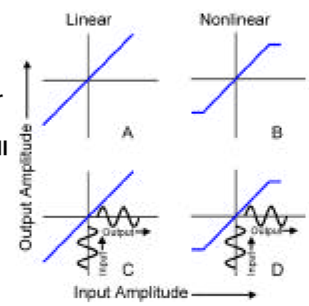
AMPLITUDE DISTORTION

- Panel A: I / O function for a <u>linear</u> system, compared with
- Panel B: I / O function for a <u>nonlinear</u> system
- Panel C: As input amplitude to <u>linear</u> system (from panel A) changes, output amplitude changes proportionally; <u>no distortion</u>



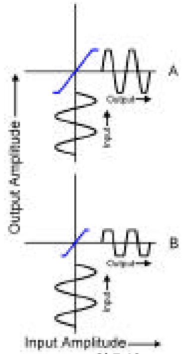
AMPLITUDE DISTORTION

- Panel D: Input amplitudes do not exceed <u>limits of linearity</u> of nonlinear system; changes in output amplitude still are <u>proportional</u> to changes in input amplitude; <u>no distortion</u>



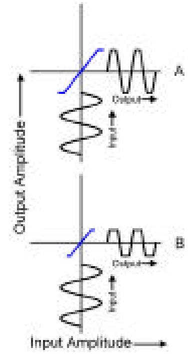
AMPLITUDE DISTORTION

- Panel A: Do some of the instantaneous amplitudes of the input signal exceed the limits of linearity of the system?
  - ☑ Yes
- What is the result?
  - ☑ The instantaneous amplitudes at or near maximum amplitude are "clipped off"-- output amplitude is not proportional to input amplitude -- the signal has been peak clipped; distortion
- Panel B: more severe peak clipping; more severe distortion



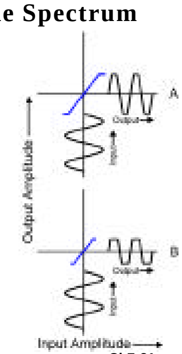
AMPLITUDE DISTORTION

- The distortion is called amplitude distortion; Why?
  - ☑ Amplitude is the waveform parameter that was altered
- Amplitude distortion is also called nonlinear distortion; Why?
  - ☑ The distortion arose from operating on the nonlinear portion of the I/O function



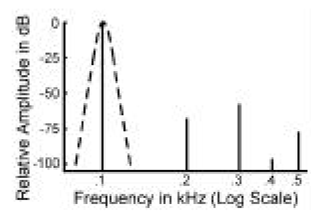
Effects of Amplitude, or Nonlinear, Distortion on Amplitude Spectrum

- Input signals in panels A & B are sinusoids
- Output signals are what kind of sound waves?
  - ☑ Complex periodic waveforms
- At what frequencies should you expect to see energy in a complex periodic waveform?
  - ☑ Harmonics
- Thus, amplitude, or nonlinear, distortion also can be called harmonic distortion (if the input waveform is sinusoidal)



Effects of Amplitude, or Nonlinear, Distortion on Amplitude Spectrum

- The figure displays the output spectrum from a nonlinear system
- At the input, f = 100 Hz
- At the output, note energy at harmonics of f_0



Percentage Harmonic Distortion

- The concept: Percentage harmonic distortion is proportion of total energy that is undesired energy
- Measure the voltage (V) of the output spectrum with a 1/3-octave filter and voltmeter
- Set f_c of the filter to equal, progressively, the frequency of each harmonic selectively
  - ♦ V_2, V_3, V_4, and V_5 reflect undesired energy
  - ♦ V_1, V_2, V_3, V_4, and V_5 reflect total energy
- Next, compute the proportion of total energy that is undesired energy

Calculation

- % = (Undesired Energy / Total Energy) × 100
  - ♦ $= \frac{f(V_2, V_3, V_4.....V_n)}{f(V_1, V_2, V_3.....V_n)} \times 100$, where

    >> f is some undefined function

    >> Vs cannot be summed

Calculation

- $= \dfrac{f'\,(V_2^2 + V_3^2 + V_4^2 + \ldots V_n^2)}{f'\,(V_1^2 + V_2^2 + V_3^2 + \ldots V_n^2)} \times 100$

  >> Vs are squared ($W \propto V^2$) so summing now permissible

- $= \dfrac{\sqrt{(V_2^2 + V_3^2 + V_4^2 + \ldots + V_n^2)}}{\sqrt{(V_1^2 + V_2^2 + V_3^2 + \ldots + V_n^2)}} \times 100$

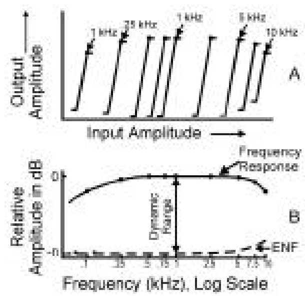
  >> Return to voltages by taking square root of sum ($V \propto \sqrt{W}$)

Approximate Percentage Harmonic Distortion

- $\% = \dfrac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \ldots + V_n^2}}{\sqrt{V_1^2}} \times 100$
- How do we justify the approximation?
- Most of total energy in denominator comes from f_0 (V_1)
- Contribution of V_2, V_3, V_4, and V_5 is usually negligible

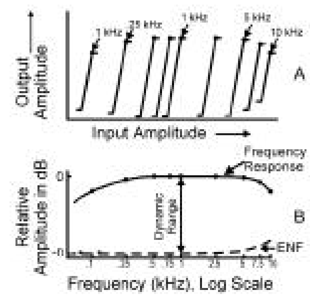
Amplitude Response and Dynamic Range

- Panel A: I / O functions for several driving frequencies from .1 kHz to 10 kHz
  - On each I / O function, location of the filled dot identifies point of maximum permissible harmonic distortion



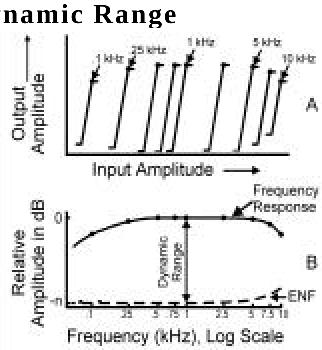
Amplitude Response and Dynamic Range

- Panel B: The dots from I / O functions are connected and redrawn in the frequency domain to form the upper curve
  - That defines the amplitude response of the system
  - Electrical noise floor (ENF) of system is shown by lower curve



Amplitude Response and Dynamic Range

- Dynamic range is distance in decibels from ENF to amplitude response at maximum
- Does ENF vary with frequency?
  - ☑ Yes



Intermodulation Distortion

- Driving signal is complex
- Experience nonlinear distortion
- Result called <u>intermodulation distortion</u>

Intermodulation Distortion

- Suppose input signal has two frequency components
  - $f_1 = 100$ Hz
  - $f_2 = 110$ Hz
- Frequency components of output signal include two types of distortion products:
  - Harmonics
  - Combination Tones
    - >> Difference tones
    - >> Summation tones

Intermodulation Distortion

- 1. Harmonics of each frequency component
  - $1f_1 = 100$ Hz & $1f_2 = 110$ Hz
  - $2f_1 = 200$ Hz & $2f_2 = 220$ Hz
  - $3f_1 = 300$ Hz & $3f_2 = 330$ Hz, etc.

Table 7-2. Examples of harmonics and combination tones produced for a complex wave with two frequency components, $f_1 = 100$ Hz and $f_2 = 110$ Hz

HARMONICS OF		COMBINATION TONES	
f_1	f_2	Difference Tones	Summation Tones
$\lvert 1f_1 + 0f_2 \rvert = 100$	$\lvert 0f_1 + 1f_2 \rvert = 110$	$\lvert 1f_1 - 1f_2 \rvert = 10$	$\lvert 1f_1 + 1f_2 \rvert = 210$
$\lvert 2f_1 + 0f_2 \rvert = 200$	$\lvert 0f_1 + 2f_2 \rvert = 220$	$\lvert 2f_1 - 1f_2 \rvert = 90$	$\lvert 2f_1 + 1f_2 \rvert = 310$
$\lvert 3f_1 + 0f_2 \rvert = 300$	$\lvert 0f_1 + 3f_2 \rvert = 330$	$\lvert 3f_1 - 1f_2 \rvert = 190$	$\lvert 3f_1 + 1f_2 \rvert = 410$
etc.	etc.	etc.	etc.

Intermodulation Distortion

- 2. Difference tones:
  - $\lvert 1f_1 - f_2 \rvert =$ 10 Hz
  - $\lvert 2f_1 - f_2 \rvert =$ 90 Hz
  - $\lvert 3f_1 - f_2 \rvert =$ 190 Hz, etc.

Table 7-2. Examples of harmonics and combination tones produced for a complex wave with two frequency components, $f_1 = 100$ Hz and $f_2 = 110$ Hz

HARMONICS OF		COMBINATION TONES	
f_1	f_2	Difference Tones	Summation Tones
$\lvert 1f_1 + 0f_2 \rvert = 100$	$\lvert 0f_1 + 1f_2 \rvert = 110$	$\lvert 1f_1 - 1f_2 \rvert = 10$	$\lvert 1f_1 + 1f_2 \rvert = 210$
$\lvert 2f_1 + 0f_2 \rvert = 200$	$\lvert 0f_1 + 2f_2 \rvert = 220$	$\lvert 2f_1 - 1f_2 \rvert = 90$	$\lvert 2f_1 + 1f_2 \rvert = 310$
$\lvert 3f_1 + 0f_2 \rvert = 300$	$\lvert 0f_1 + 3f_2 \rvert = 330$	$\lvert 3f_1 - 1f_2 \rvert = 190$	$\lvert 3f_1 + 1f_2 \rvert = 410$
etc.	etc.	etc.	etc.

Intermodulation Distortion

- 3. Summation tones:
  - $1f_1 + f_2 = 210$ Hz
  - $2f_1 + f_2 = 310$ Hz
  - $3f_1 + f_2 = 410$ Hz, etc.

Table 7-2. Examples of harmonics and combination tones produced for a complex wave with two frequency components, $f_1 = 100$ Hz and $f_2 = 110$ Hz

HARMONICS OF		COMBINATION TONES	
f_1	f_2	Difference Tones	Summation Tones
$\lvert 1f_1 + 0f_2 \rvert = 100$	$\lvert 0f_1 + 1f_2 \rvert = 110$	$\lvert 1f_1 - 1f_2 \rvert = 10$	$\lvert 1f_1 + 1f_2 \rvert = 210$
$\lvert 2f_1 + 0f_2 \rvert = 200$	$\lvert 0f_1 + 2f_2 \rvert = 220$	$\lvert 2f_1 - 1f_2 \rvert = 90$	$\lvert 2f_1 + 1f_2 \rvert = 310$
$\lvert 3f_1 + 0f_2 \rvert = 300$	$\lvert 0f_1 + 3f_2 \rvert = 330$	$\lvert 3f_1 - 1f_2 \rvert = 190$	$\lvert 3f_1 + 1f_2 \rvert = 410$
etc.	etc.	etc.	etc.

Combination Tones

- Equation 7.3 defines frequencies of all harmonics, difference tones, and summation tones
  - $mf_1 \pm nf_2$, where
  - m and n are assigned all integer values