ECE-2025 Fall-2009

Lecture 5
Spectrum Representation
31-Aug-09

General Info

- **t-square** has all **OFFICIAL** msgs
- ON-Line Peer Evaluation Form (for Lab)
- Check wiki for current office hours times
  - Some are changing
- HW, Lab and MATLAB Help:
  - Mon, Tues, Wed: 6pm Klaus-2440
    - Weekly during the semester
- No classes Monday, 7-Sept, Labor Day

Lab Info

- Lab #1 Report (one per team)
  - Turn in at beginning of your lab time
  - Peer Evaluation, one for each student
  - **Ask your grading TA about his/her format**
- Lab #2 is posted
  - Monday sections **only**
    - start Lab #2 on 31-Aug, and turn it in on 14-Sept
- Finish Instructor Verification in Lab
  - Come to lab PREPARED
- Computer Problems? **help@ece.gatech.edu**

Homework Info

- Written HW #2 due this week
  - Due in Recitation, at the beginning
  - Format your HW (see guidelines)
  - 2-part Solution Format
  - Monday sections **only**
    - Turn in HW #3 during your Wednesday lab next week
- HW #1 Solutions are posted
- HW #3 also posted

HISTORY

- Which company's first successful product was a sine-wave generator?
  - Variable frequency
  - Lab Instrument

HEWLETT PACKARD Agilent

Lecture

READING ASSIGNMENTS

- This Lecture:
  - Chapter 3, Section 3-1
- Other Reading:
  - Appendix A: Complex Numbers
  - Next Lecture: Ch 3, Sects 3-2, 3-3, 3-7 & 3-8

LECTURE OBJECTIVES

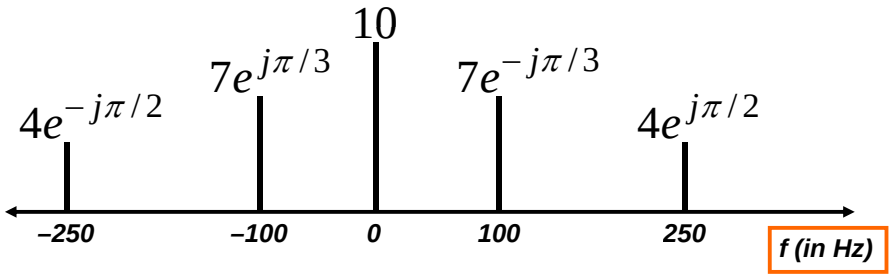
- Sinusoids with DIFFERENT Frequencies
  - SYNTHESIZE by Adding Sinusoids

$$x(t) = \sum_{k=1}^{N} A_k \cos(2\pi f_k t + \varphi_k)$$

- SPECTRUM Representation
  - Graphical Form shows **DIFFERENT** Freqs

FREQUENCY DIAGRAM

- Want to visualize relationship between frequencies, amplitudes and phases
- Plot Complex Amplitude vs. Freq



Another FREQ. Diagram

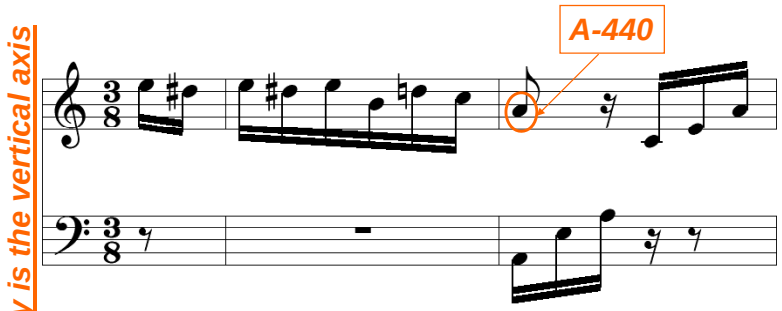


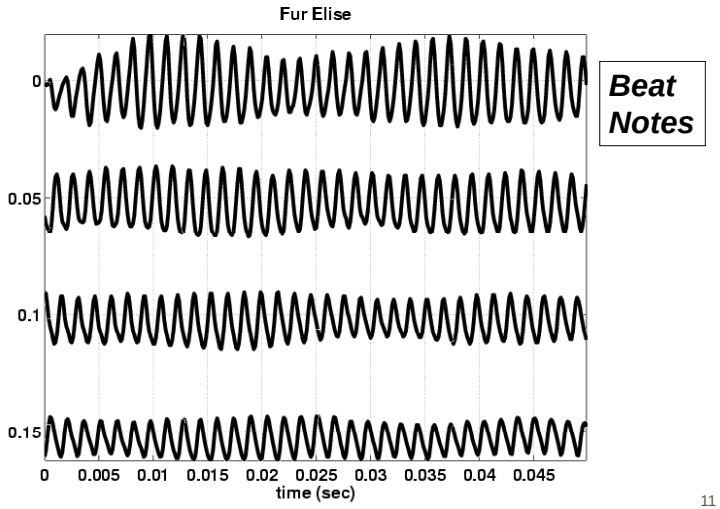
Figure 3.18 Sheet-music notation is a time–frequency diagram.

Time is the horizontal axis

MOTIVATION

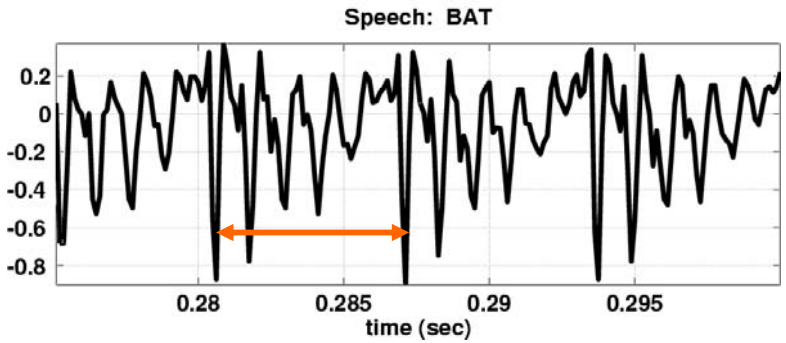
- Synthesize Complicated Signals
  - Musical Notes
    - Piano uses 3 strings for many notes
    - Chords: play several notes simultaneously
  - Human Speech
    - Vowels have dominant frequencies
    - Application: computer generated speech
  - Can all signals be generated this way?
    - Sum of sinusoids?

Fur Elise WAVEFORM



Speech Signal: BAT

- Nearly **Periodic** in Vowel Region
  - Period is (Approximately) T = 0.0065 sec



INVERSE Euler's Formula

- What is the "spectrum" representation for a single sinusoid?
- Solve Euler's formula for cosine (or sine)

$$\cos(\omega t) = \frac{1}{2}(e^{j\omega t} + e^{-j\omega t})$$

$$\sin(\omega t) = \frac{1}{2j}(e^{j\omega t} - e^{-j\omega t})$$

SPECTRUM Interpretation

- Cosine = sum of 2 complex exponentials:

$$A\cos(7t) = \frac{A}{2}e^{j7t} + \frac{A}{2}e^{-j7t}$$

  - One has a positive frequency
  - The other has negative freq.
  - Amplitude of each is half as big

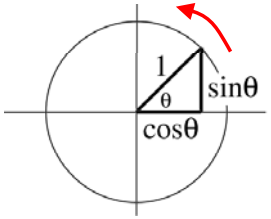
NEGATIVE FREQUENCY

- Is negative frequency real?
- Doppler Radar provides intuition
  - Police radar measures speed by using the Doppler shift principle
  - Let's assume 400Hz ←→60 mph
  - +400Hz means towards the radar
  - -400Hz means away (opposite direction)
  - Think of a train whistle

Negative Frequency is still a rotating phasor

$$e^{j\omega t} = \cos(\omega t) + j\sin(\omega t)$$

- View as vector rotating counterclockwise
  - $\theta = \omega t$
  - Angle changes vs. time



Negative frequency ➔ clockwise rotation

Phasor cancellation

$$\cos(\omega t) = \frac{1}{2}(e^{j\omega t} + e^{-j\omega t})$$

- Interpretation: cosine is sum of two vectors rotating in opposite directions at same speed

General form of cosine spectrum

- General form:

$$A\cos(\omega t + \phi)$$

$$= \frac{A}{2}e^{j\phi}e^{j\omega t} + \frac{A}{2}e^{-j\phi}e^{-j\omega t}$$

  - Amplitudes are multiplied by ½
  - Complex amplitudes are complex conjugates
    - Called ***conjugate symmetry***

SPECTRUM of SINE

- Sine = sum of 2 complex exponentials:

$$A\sin(7t) = \frac{A}{2j}e^{j7t} - \frac{A}{2j}e^{-j7t}$$

$$= \frac{1}{2}Ae^{-j0.5\pi}e^{j7t} + \frac{1}{2}Ae^{j0.5\pi}e^{-j7t}$$

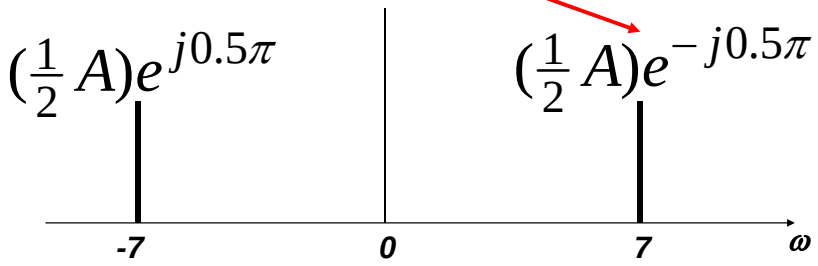
$$\frac{-1}{j} = j = e^{j0.5\pi}$$

  - Positive freq. has phase = -0.5π
  - Negative freq. has phase = +0.5π

GRAPHICAL SPECTRUM

EXAMPLE of SINE

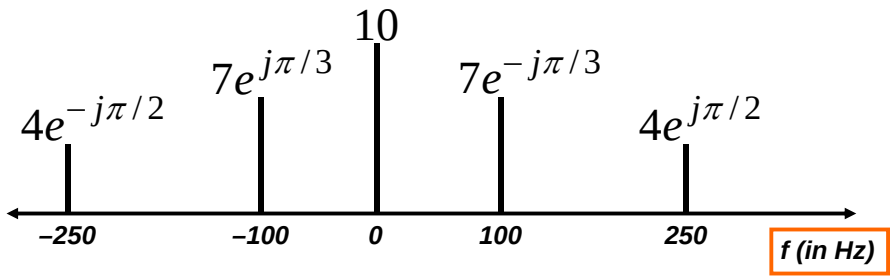
$$A\sin(7t) = \frac{1}{2}Ae^{-j0.5\pi}e^{j7t} + \frac{1}{2}Ae^{j0.5\pi}e^{-j7t}$$



AMPLITUDE, PHASE & FREQUENCY are shown

SPECTRUM ---> SINUSOID

- Add the spectrum components:



What is the formula for the signal x(t)?

Gather (A,ω,ϕ) information

- Frequencies:
  - -250 Hz
  - -100 Hz
  - **0** Hz
  - 100 Hz
  - 250 Hz
- Amplitude & Phase
  - 4 -π/2
  - 7 +π/3
  - 10 **0**
  - 7 -π/3
  - 4 +π/2

*Note the **conjugate phase***

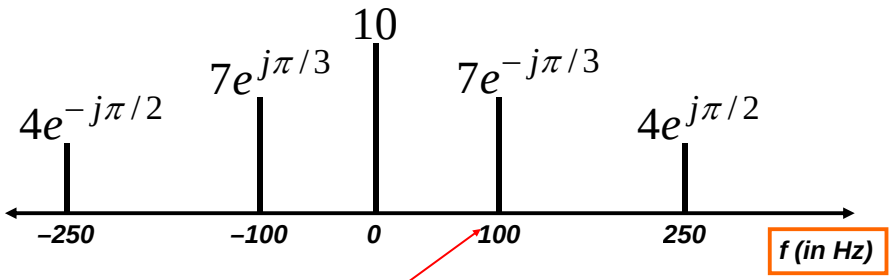
***DC** is another name for zero-freq component*
***DC** component always has **ϕ=0** or **π** (for real **x(t)**)*

Add Spectrum Components-1

- **Frequencies:**
  - **-250 Hz**
  - **-100 Hz**
  - **0 Hz**
  - **100 Hz**
  - **250 Hz**
- **Amplitude & Phase**
  - **4 -π/2**
  - **7 +π/3**
  - **10 0**
  - **7 -π/3**
  - **4 +π/2**

$$x(t) = 10 + 7e^{-j\pi/3}e^{j2\pi(100)t} + 7e^{j\pi/3}e^{-j2\pi(100)t}$$
$$4e^{j\pi/2}e^{j2\pi(250)t} + 4e^{-j\pi/2}e^{-j2\pi(250)t}$$

Add Spectrum Components-2



$$x(t) = 10 + 7e^{-j\pi/3}e^{j2\pi(100)t} + 7e^{j\pi/3}e^{-j2\pi(100)t}$$
$$4e^{j\pi/2}e^{j2\pi(250)t} + 4e^{-j\pi/2}e^{-j2\pi(250)t}$$

Simplify Components

$$x(t) = 10 + 7e^{-j\pi/3}e^{j2\pi(100)t} + 7e^{j\pi/3}e^{-j2\pi(100)t} + 4e^{j\pi/2}e^{j2\pi(250)t} + 4e^{-j\pi/2}e^{-j2\pi(250)t}$$

Use Euler's Formula to get REAL sinusoids:

$$A\cos(\omega t + \varphi) = \tfrac{1}{2}Ae^{j\varphi}e^{j\omega t} + \tfrac{1}{2}Ae^{-j\varphi}e^{-j\omega t}$$

FINAL ANSWER

$$x(t) = 10 + 14\cos(2\pi(100)t - \pi/3) + 8\cos(2\pi(250)t + \pi/2)$$

So, we get the general form:

$$x(t) = A_0 + \sum_{k=1}^{N} A_k \cos(2\pi f_k t + \varphi_k)$$

Summary: GENERAL FORM

$$x(t) = A_0 + \sum_{k=1}^{N} A_k \cos(2\pi f_k t + \varphi_k)$$

$$x(t) = X_0 + \sum_{k=1}^{N} \Re\{A_k e^{j\varphi_k} e^{j2\pi f_k t}\}$$

$$X_k = A_k e^{j\varphi_k}$$

Frequency $= f_k$

$$\Re\{z\} = \tfrac{1}{2}z + \tfrac{1}{2}z^*$$

$$x(t) = X_0 + \sum_{k=1}^{N} \{\tfrac{1}{2}X_k e^{j2\pi f_k t} + \tfrac{1}{2}X_k^* e^{-j2\pi f_k t}\}$$

Example: Synthetic Vowel

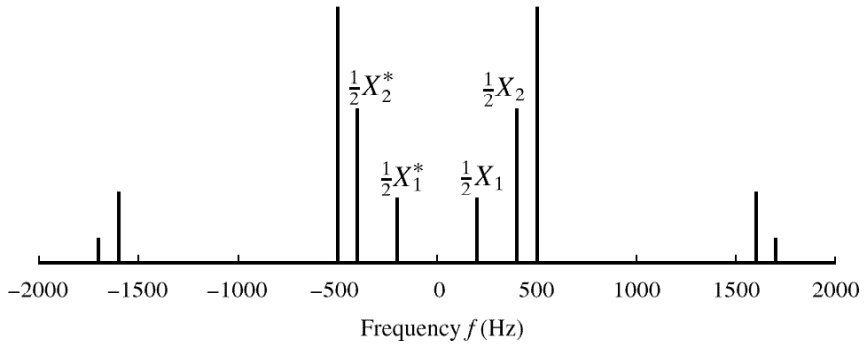
- Sum of 5 Frequency Components

f_k (Hz)	X_k	Mag	Phase (rad)
200	$(771 + j12202)$	12,226	1.508
400	$(-8865 + j28048)$	29,416	1.876
500	$(48001 - j8995)$	48,836	−0.185
1600	$(1657 - j13520)$	13,621	−1.449
1700	$4723 + j0$	4723	0

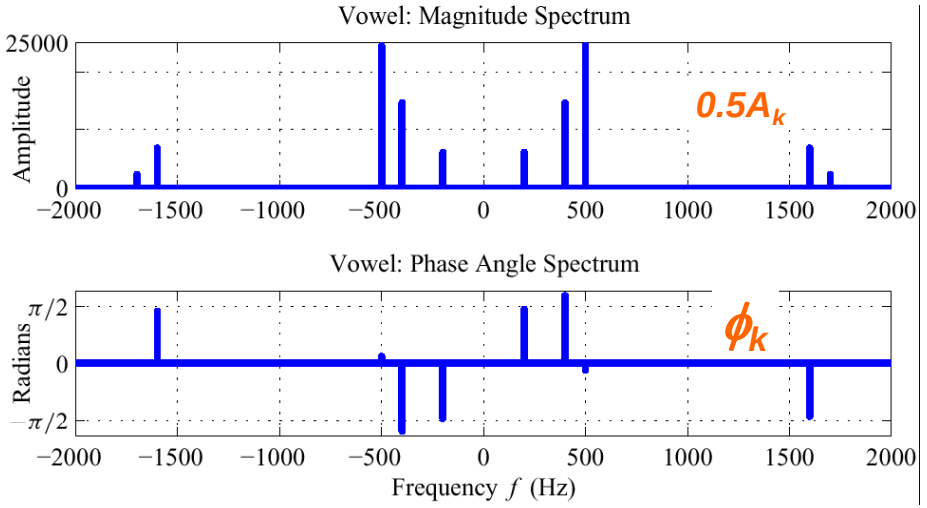
Table 3.1: Complex amplitudes for harmonic signal that approximates the vowel sound "ah".

SPECTRUM of VOWEL

- Note: Spectrum has $0.5X_k$ (except X_{DC})
- Conjugates in negative frequency



SPECTRUM of VOWEL (Polar Format)



Vowel Waveform (sum of all 5 components)

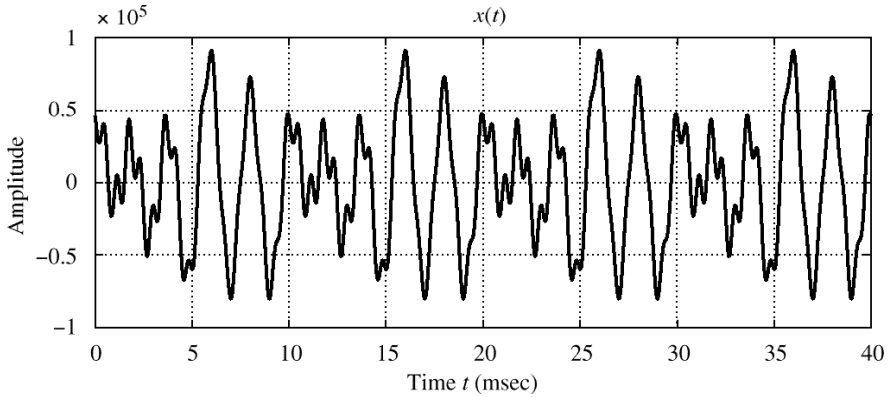


Figure 3.11 Sum of all of the terms in (3.3.4). Note that the period is 10 msec, which equals $1/f_0$.