

# Math 211

Lecture #34

Inhomogeneous Equations  
Forced Harmonic Motion

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## Inhomogeneous Equations

**Theorem:** Assume

- $y_p(t)$  is a particular solution to the inhomogeneous equation  $y'' + py' + qy = f(t)$ ;
- $y_1(t)$  &  $y_2(t)$  is a fundamental set of solutions to the homogeneous equation  $y'' + py' + qy = 0$ .

Then the general solution to the inhomogeneous equation is

$$y(t) = y_p(t) + C_1y_1(t) + C_2y_2(t).$$

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## Method of Undetermined Coefficients

$$y'' + py' + qy = f(t)$$

The mantra for finding a particular solution is as follows:

- If the forcing term  $f(t)$  has a form which is replicated under differentiation, then look for a particular solution of the same general form as the forcing term.

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## Exponential Forcing Term

$$y'' + py' + qy = Ce^{bt}$$

- Example:  $y'' + 3y' + 2y = 4e^{-3t}$
- Try  $y_p(t) = ae^{-3t}$ ,  $a$  to be determined.
  - ♦ Particular solution:  $y_p(t) = 2e^{-3t}$ .
- Homogeneous equation:  $y'' + 3y' + 2y = 0$ .
  - ♦ Fundamental set of solutions:  $e^{-2t}$  &  $e^{-t}$ .
- General solution to the inhomogeneous equation:

$$y(t) = 2e^{-3t} + C_1e^{-t} + C_2e^{-2t}.$$

[Return](#)

## Trigonometric Forcing Term

$$y'' + py' + qy = A \cos \omega t + B \sin \omega t$$

- Example:  $y'' + 4y' + 5y = 4 \cos 2t - 3 \sin 2t$
- Try  $y_p(t) = a \cos 2t + b \sin 2t$ 
  - ♦ Particular solution:  $y_p(t) = [28 \cos 2t + 29 \sin 2t]/65$ .
- Homogeneous equation:  $y'' + 4y' + 5y = 0$ 
  - ♦ Fund. set of sol'ns:  $e^{-2t} \cos t$  &  $e^{-2t} \sin t$ .
- General solution to the inhomogeneous equation:

$$y(t) = \frac{28 \cos 2t + 29 \sin 2t}{65} + e^{-2t}[C_1 \cos t + C_2 \sin t].$$

[Return](#)

## Complex Method

$$x'' + px' + qx = A \cos \omega t \quad \text{or}$$

$$y'' + py' + qy = A \sin \omega t.$$

- Solve  $z'' + pz' + qz = Ae^{i\omega t}$ .
  - ♦ Try  $z(t) = ae^{i\omega t}$ .
- Then

$$x_p(t) = \operatorname{Re}(z(t)) \quad \text{and}$$

$$y_p(t) = \operatorname{Im}(z(t)).$$

[Return](#)

[Trigonometric forcing](#)

### Example

$$x'' + 4x' + 5x = 4 \cos 2t$$

- Solve  $z'' + 4z' + 5z = 4e^{2it}$ .
  - ♦ Try  $z(t) = ae^{2it}$ .
  - ♦ Particular solution:  $z(t) = (4 - 32i)e^{2it}/65$ .
- Particular solution to the real equation:

$$\begin{aligned} x_p(t) &= \operatorname{Re}(z(t)) \\ &= [4 \cos 2t + 32 \sin 2t] / 65. \end{aligned}$$

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### Polynomial Forcing Term

$$y'' + py' + qy = P(t)$$

- Example:  $y'' - 3y' + 2y = 1 - 4t$ .
  - ♦ Try  $y(t) = a + bt$ .
  - ♦ Particular solution:  $y(t) = -5 - 2t$ .
- General solution

$$y(t) = -5 - 2t + C_1 e^t + C_2 e^{2t}.$$

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### Exceptional Cases

- Example:  $y'' - 3y' + 2y = 3e^t$ .
  - ♦ Try  $y(t) = ae^t$
  - ♦ The method does not work because  $e^t$  is a solution to the associated homogeneous equation.
- Try  $y(t) = ate^t$ 
  - ♦ Particular solution:  $y_p(t) = -3te^t$ .
- General solution:  $y(t) = -3te^t + C_1 e^t + C_2 e^{2t}$ .
- If the suggested particular solution does not work, multiply it by  $t$  and try again.

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## Combination Forcing Term

Example  $y'' + 5y' + 6y = 2e^{2t} - 5 \cos t$

- Solve

$$y_1'' + 5y_1' + 6y_1 = 2e^{2t}$$

$$y_2'' + 5y_2' + 6y_2 = -5 \cos t$$

- Set  $y(t) = y_1(t) + y_2(t)$ .

[Theorem](#)

[Previous](#)

[UDC](#)

## Forced Harmonic Motion

Assume an oscillatory forcing term:

$$y'' + 2cy' + \omega_0^2 y = A \cos \omega t$$

- $A$  is the forcing amplitude
- $\omega$  is the forcing frequency
- $\omega_0$  is the natural frequency.
- $c$  is the damping constant.

[Return](#)

## Forced Undamped Motion

$$y'' + \omega_0^2 y = A \cos \omega t$$

- Homogeneous equation

$$y'' + \omega_0^2 y = 0$$

- General solution

$$y(t) = C_1 \cos \omega_0 t + C_2 \sin \omega_0 t.$$

- If  $\omega = \omega_0$  we have an exceptional case.

[Return](#)

- $\omega \neq \omega_0$

$$y'' + \omega_0^2 y = A \cos \omega t$$

- ♦ Look for a particular solution of the form

$$x_p(t) = a \cos \omega t + b \sin \omega t.$$

- ♦ We find

$$x_p(t) = \frac{A}{\omega_0^2 - \omega^2} \cos \omega t.$$

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- $\omega \neq \omega_0$

- ♦ General solution

$$x(t) = C_1 \cos \omega_0 t + C_2 \sin \omega_0 t + \frac{A}{\omega_0^2 - \omega^2} \cos \omega t.$$

- ♦ Initial conditions  $x(0) = x'(0) = 0 \Rightarrow$

$$x(t) = \frac{A}{\omega_0^2 - \omega^2} [\cos \omega t - \cos \omega_0 t].$$

- ♦ Example:  $\omega_0 = 9$ ,  $\omega = 8$ ,  $A = \omega_0^2 - \omega^2 = 17$ .

$$x(t) = \cos 9t - \cos 8t.$$

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Homogeneous

Inhomogeneous

- $\omega \neq \omega_0$

- ♦ Set  $\bar{\omega} = \frac{\omega_0 + \omega}{2}$  and  $\delta = \frac{\omega_0 - \omega}{2}$ .

$$\Rightarrow \omega = \bar{\omega} - \delta \quad \text{and} \quad \omega_0 = \bar{\omega} + \delta, \quad \text{and}$$

$$\begin{aligned} x(t) &= \frac{A}{\omega_0^2 - \omega^2} [\cos \omega t - \cos \omega_0 t] \\ &= \frac{A \sin \delta t}{2\bar{\omega}\delta} \sin \bar{\omega} t. \end{aligned}$$

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ICsol

- $\omega \neq \omega_0$

- ♦ Example:

$$\bar{\omega} = 8.5 \quad \text{and} \quad \delta = 0.5.$$

- ♦ Envelope: Slow oscillation with frequency  $\delta$ ,

$$\pm \left| \frac{A \sin \delta t}{2\bar{\omega}\delta} \right|.$$

- ♦ Fast oscillation with frequency  $\bar{\omega}$  and varying amplitude.
- ♦ Beats.

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- $\omega = \omega_0$

$$y'' + \omega_0^2 y = A \cos \omega_0 t.$$

- ♦ We have an exceptional case. Try

$$x_p(t) = t[a \cos \omega t + b \sin \omega t].$$

- ♦ We find

$$x_p(t) = \frac{A}{2\omega_0} t \sin \omega_0 t.$$

- ♦ General solution

$$x(t) = C_1 \cos \omega_0 t + C_2 \sin \omega_0 t + \frac{A}{2\omega_0} t \sin \omega_0 t.$$

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- $\omega = \omega_0$

- ♦ Initial conditions  $x(0) = x'(0) = 0 \Rightarrow$

$$x(t) = \frac{A}{2\omega_0} t \sin \omega_0 t.$$

- ▶ Example:  $\omega_0 = 5$ , and  $A = 2\omega_0 = 10$ .

$$x(t) = t \sin 5t.$$

- ♦ Oscillation with increasing amplitude.
- ♦ First example of *resonance*.
  - ▶ Forcing at the natural frequency can cause oscillations that grow out of control.

Return