Math 211

Lecture #34

Forced Harmonic Motion

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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.
Forced Undamped Harmonic Motion

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

- Homogeneous equation: \( y'' + \omega_0^2 y = 0 \).
  - General solution: \( y(t) = C_1 \cos \omega_0 t + C_2 \sin \omega_0 t \).
- \( \omega \neq \omega_0 \): Look for \( x_p(t) = a \cos \omega t + b \sin \omega t \).
  - We find \( x_p(t) = \frac{A}{\omega_0^2 - \omega^2} \cos \omega t \).
  - General solution:
    \[ x(t) = C_1 \cos \omega_0 t + C_2 \sin \omega_0 t + \frac{A}{\omega_0^2 - \omega^2} \cos \omega t. \]
\( \omega \neq \omega_0 \) (cont.)

- 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: \( \omega_0 = 9, \omega = 8, A = \omega_0^2 - \omega^2 = 17. \)

♦ Set \( \overline{\omega} = \frac{\omega_0 + \omega}{2} \) and \( \delta = \frac{\omega_0 - \omega}{2}. \)

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

\[
= \frac{A \sin \delta t}{2 \omega \delta} \sin \overline{\omega} t.
\]

▷ Example: \( \overline{\omega} = 8.5 \) and \( \delta = 0.5. \)
• $\omega \neq \omega_0$ (cont.)

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

\[
= \frac{A \sin \delta t}{2\omega \delta} \sin \bar{\omega} t.
\]

♦ The \textit{envelope} $\pm \left| \frac{A \sin \delta t}{2\omega \delta} \right|$ oscillates slowly with frequency $\delta$.

♦ The solution $x(t)$ shows a fast oscillation with frequency $\bar{\omega}$ and amplitude defined by the envelope.

♦ This phenomenon is called \textit{beats}. It occurs whenever two oscillations with frequencies that are close interfere.
\( \omega = \omega_0 \)

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

\( \diamond \) This is an exceptional case. Try

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

\( \diamond \) We find

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

\( \diamond \) General solution

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

  - **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.
Forced, Damped Harmonic Motion

\[ x'' + 2cx' + \omega_0^2 x = A \cos \omega t \]

Use the complex method.

- Solve \( z'' + 2cz' + \omega_0^2 z = Ae^{i\omega t} \).
- We try \( z(t) = ae^{i\omega t} \) and get

\[
z'' + 2cz' + \omega_0^2 z = [(i\omega)^2 + 2c(i\omega) + \omega_0^2]ae^{i\omega t}
= P(i\omega)z
\]

where \( P(\lambda) = \lambda^2 + 2c\lambda + \omega_0^2 \) is the characteristic polynomial.

- The complex solution is \( z(t) = \frac{1}{P(i\omega)} Ae^{i\omega t} \).
- The real solution is \( x_p(t) = \text{Re}(z(t)) \).
Example

\[ x'' + 5x' + 4x = 50 \cos 3t \]

- \( P(\lambda) = \lambda^2 + 5\lambda + 4. \)
  - \( P(i\omega) = P(3i) = -5 + 15i \)
- \( z(t) = \frac{1}{P(i\omega)} \cdot 50e^{3it} \)
  \[ = -[(\cos 3t - 3 \sin 3t) + i(\sin 3t + 3 \cos 3t)] \]
- \( x_p(t) = \text{Re}(z(t)) = 3 \sin 3t - \cos 3t. \)
The Transfer Function

- The complex solution is

\[ z(t) = \frac{1}{P(i\omega)} A e^{i\omega t} = H(i\omega) A e^{i\omega t}, \]

where \( H(i\omega) = \frac{1}{P(i\omega)} \) is called the transfer function.

- We will use complex polar coordinates to write

\[ H(i\omega) = G(\omega) e^{-i\phi(\omega)}, \]

where \( G(\omega) = |H(i\omega)| \) is the called the gain and \( \phi(\omega) \) is called the phase shift.
The Gain and Phase Shift

- If \( P(\lambda) = \lambda^2 + 2c\lambda + \omega_0^2 \) is the characteristic polynomial, then \( P(i\omega) = Re^{i\phi} \), where

\[
R = \sqrt{(\omega_0^2 - \omega^2)^2 + 4c^2\omega^2}, \quad \text{and}
\]

\[
\phi = \arccot\left(\frac{\omega_0^2 - \omega^2}{2c\omega}\right).
\]

- The transfer function is

\[
H(i\omega) = \frac{1}{P(i\omega)} = \frac{1}{R}e^{-i\phi} = G(\omega)e^{-i\phi}.
\]

- The gain \( G(\omega) = \frac{1}{R} = \frac{1}{\sqrt{(\omega_0^2 - \omega^2)^2 + 4c^2\omega^2}}.\)
• The complex particular solution is

\[ z(t) = H(i\omega)Ae^{i\omega t} = G(\omega)e^{-i\phi} \cdot Ae^{i\omega t} \]

\[ = G(\omega)Ae^{i(\omega t - \phi)}. \]

• The real particular solution is

\[ x_p(t) = \operatorname{Re}(z(t)) = G(\omega)A \cos(\omega t - \phi). \]

♦ The amplitude of \( x_p \) is \( G(\omega)A \), and the phase is \( \phi \).
The general solution is

\[ x(t) = x_p(t) + x_h(t) \]

\[ = G(\omega)A \cos(\omega t - \phi) + x_h(t), \]

where \( x_h(t) \) is the general solution of the homogeneous equation.

\( x_h(t) \rightarrow 0 \) as \( t \) increases, so \( x_h \) is called the \textit{transient term}.

\( x_p(t) = G(\omega)A \cos(\omega t - \phi) \) is called the \textit{steady-state solution}. 
Example

\[ x'' + 5x' + 4x = 50 \cos 3t \]

\[ G(\omega) = \frac{1}{\sqrt{(4 - \omega^2)^2 + 25\omega^2}} \] and

\[ \phi = \arccot \left( \frac{4 - \omega^2}{5\omega} \right). \]

♦ With \( \omega = 3 \),

\[ G(3) = \frac{1}{5\sqrt{10}} \approx 0.0632 \]

\[ \phi = \arccot(-3/5) \approx 2.1112. \]

♦ SS solution \( x_p(t) = G(3) A \cos(3t - \phi). \)
The Steady-State Solution

\[ x_p(t) = G(\omega)A \cos(\omega t - \phi). \]

- The forcing function is \( A \cos \omega t \).
- Properties of the steady-state response:
  - It is oscillatory at the driving frequency.
  - The amplitude is the product of the gain, \( G(\omega) \), and the amplitude of the forcing function.
  - It has a phase shift of \( \phi \) with respect to the forcing function.
The Gain

\[ G(\omega) = \frac{1}{\sqrt{(\omega_0^2 - \omega^2)^2 + 4c^2\omega^2}} \]

Set \( \omega = s\omega_0 \) and \( c = D\omega_0 / 2 \) (or \( s = \omega / \omega_0 \) and \( D = 2c / \omega_0 \)). Then

\[ G(\omega) = \frac{1}{\omega_0^2} \frac{1}{\sqrt{(1 - s^2)^2 + D^2s^2}} \]