

## Module 12 - Second Order Time Response

ME3050 - Dynamics Modeling and Controls

Mechanical Engineering

Tennessee Technological University

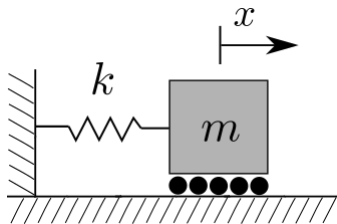
### Topic 2 - The Damping Ratio

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- The Damped Natural Frequency
- The Overdamped Case
- The Critically Damped Case
- The Underdamped Case

## Mass Spring Model

Consider the mass-spring system without damping.



The EOM is:

$$m\ddot{x} + kx = 0 \text{ with}$$

$$x(t = 0) = x_0, \text{ and } v(t = 0) = v_0$$

## Solution with Laplace Transforms Method

Solve for  $x(t)$  with a method of your choice.

$$x(t) = \frac{v_0}{\omega_n} \sin(\omega_n t) + x_0 \cos(\omega_n t) \text{ with } \omega_n = \sqrt{\frac{k}{m}}$$

## Phase Shift

The solution is commonly written as a single oscillating term with a **phase shift**  $\phi$ .

$$x(t) = \frac{v_0}{\omega_n} \sin(\omega_n t) + x_0 \cos(\omega_n t) \quad \text{with} \quad \omega_n = \sqrt{\frac{k}{m}}$$

Is equivalent to:

$$x(t) = A \cos(\omega_n t - \phi) \quad A = \sqrt{x_0^2 + \left[\frac{v_0}{\omega_n}\right]^2} \quad \phi = \tan^{-1}\left(\frac{v_0}{x_0 \omega_n}\right)$$

Sine could be used instead.

$$x(t) = A \sin(\omega_n t + \phi) \quad A = \sqrt{x_0^2 + \left[\frac{v_0}{\omega_n}\right]^2} \quad \phi = \tan^{-1}\left(\frac{x(0)\omega_n}{v_0}\right)$$

## Sketch of Free Response

Sketch the **free** response in the time domain.

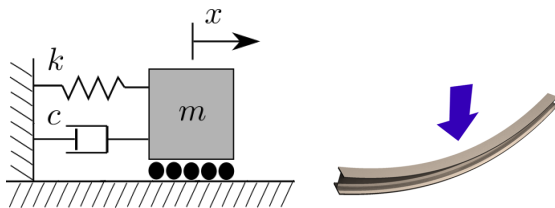
$$\begin{aligned}x(t) &= \frac{v_0}{\omega_n} \sin(\omega_n t) + x_0 \cos(\omega_n t) \\&= A \cos(\omega_n t - \phi) \text{ with } \phi = \tan^{-1}\left(\frac{v_0}{x_0 \omega_n}\right)\end{aligned}$$



Is this a stable system? What does the phase shift  $\phi$  represent?

## Second Order System with Damping

Now, consider the mass-spring system with damping present.



The EOM is:

$$m\ddot{x} + c\dot{x} + kx = 0 \text{ with}$$

$$x(t = 0) = x_0, \text{ and } v(t = 0) = v_0$$

## Solution with Trial Solution Method

The trial solution method is used to derive the response equation in terms of the system variables and parameters.

$$m\ddot{x} + c\dot{x} + kx = 0 \implies (mr^2 + cr + k)Ae^{rt} = 0$$

You can see the *characteristic equation* becomes:

$$(mr^2 + cr + k) = 0$$

Solve for the roots. In system dynamics they are called  $s_{1,2}$

$$r_{1,2} = s_{1,2} = \frac{-c \pm \sqrt{c^2 - 4mk}}{2m} = -\frac{c}{2m} \pm \sqrt{\left(\frac{c}{2m}\right)^2 - \frac{k}{m}}$$



## The Roots of the System

The roots of the system determine the behavior.

$$s_{1,2} = \frac{-c \pm \sqrt{c^2 - 4mk}}{2m}$$

The **discriminant**  $c^2 - 4mk$  drives the *case* in the trial solution method.

- IF \_\_\_\_\_  $\implies$  Case 1: Distinct and Real
- IF \_\_\_\_\_  $\implies$  Case 2: Repeated and Real
- IF \_\_\_\_\_  $\implies$  Case 3: Complex Conjugate Pair

## Damping Cases and the Critical Damping Value

In a system with known mass and spring constant, the damping value determines the behavior. The damping value that causes the *discriminant* to equal zero (case 2) is the **critical damping value**.

$$c^2 - 4mk = 0 \implies c = \sqrt{4mk} = 2\sqrt{mk}$$

$$c_{critical} = 2\sqrt{mk}$$

## The Damping Ratio

The damping ratio  $\zeta$  is the ratio of damping  $c$  to the critical damping value  $c_{critical}$ .

$$\zeta = \frac{c}{c_{critical}} = \frac{c}{2\sqrt{mk}}$$

Re-write the roots with this new quantity.

$$s_{1,2} = -\zeta\omega_n \pm \omega_n\sqrt{\zeta^2 - 1} = -\zeta\omega_n \pm j\omega_n\sqrt{1 - \zeta^2}$$

We define a new quantity, **damped natural frequency**.

$$\omega_d = \omega_n\sqrt{1 - \zeta^2}$$

Now re-write the roots again in terms of  $\zeta$  and  $\omega_d$ .

$$s_{1,2} = \zeta\omega_n \pm j\omega_d$$

## Forms of the Response Equations

The behavior of the system depends on the damping ratio.

Case 1	$c > 2\sqrt{mk}$	<b>Overdamped</b>	$\zeta > 1$
Case 2	$c = 2\sqrt{mk} = c_{critical}$	<b>Critically Damped</b>	$\zeta = 1$
Case 3	$c < 2\sqrt{mk}$	<b>Underdamped</b>	$\zeta < 1$

## The Overdamped Case

The roots are real and distinct and the system *does not* oscillate.

Overdamped  $c > 2\sqrt{mk} \implies \zeta > 1$

$$s_{1,2} = -\zeta \pm \omega_n \sqrt{\zeta^2 - 1}$$

$$x(t) = C_1 e^{(-\zeta\omega_n + \omega_n \sqrt{\zeta^2 - 1})t} + C_2 e^{(-\zeta\omega_n - \omega_n \sqrt{\zeta^2 - 1})t}$$

$$x(t) = e^{-\zeta\omega_n t} \{ C_1 e^{\omega_n \sqrt{\zeta^2 - 1}t} + C_2 e^{-\omega_n \sqrt{\zeta^2 - 1}t} \}$$

$$C_1 = \frac{-v_0 + (-\zeta + \sqrt{\zeta^2 - 1})\omega_n x_0}{2\omega_n \sqrt{\zeta^2 - 1}} \quad C_2 = \frac{-v_0 + (\zeta + \sqrt{\zeta^2 - 1})\omega_n x_0}{2\omega_n \sqrt{\zeta^2 - 1}}$$

## The Critically Damped Case

The roots are real and repeated and the system *does not* oscillate.

Critically Damped  $c = 2\sqrt{mk} \implies \zeta = 1$

$$s_{1,2} = \frac{-c}{2m} = \zeta\omega_n = -\omega_n$$

$$x(t) = C_1 e^{-\omega_n t} + C_2 t e^{-\omega_n t}$$

$$\dot{x} = -\omega_n C_1 e^{-\omega_n t} + C_2 t (-\omega_n e^{-\omega_n t}) + e^{-\omega_n t} (C_2)$$

$$x(t=0) = x_0 \implies C_1 = x_0$$

$$v(t=0) = v_0 \implies v_0 = -\omega_n C_1 + 0 + (1)C_2 \implies C_2 = v_0 + \omega_n x_0$$

## The Underdamped Case

The roots are a complex conjugate pair and the system oscillates.

Underdamped  $c < 2\sqrt{mk} \implies \zeta < 1$

$$s_{1,2} = -\zeta\omega_n \pm j\omega_d$$

$$x(t) = C_1 e^{(\zeta\omega_n + j\omega_d)t} + C_2 e^{(\zeta\omega_n - j\omega_d)t}$$

$$x(t) = e^{-\zeta\omega_n t} \{ A \cos(\omega_d t) + B \sin(\omega_d t) \}$$

Use the initial position to solve for the first unknown.

$$x(t=0) = x_0 = (1)(A(1) + B(0)) \implies A = x_0$$

## The Underdamped Case

Take the derivative and solve for the second unknown.

$$x(t) = e^{-\zeta\omega_n t} \{A \cos(\omega_d t) + B \sin(\omega_d t)\}$$

$$\begin{aligned} \dot{x}(t) &= e^{-\zeta\omega_n t} (-\omega_d A \sin(\omega_d t)) + A \cos(\omega_d t) (-\zeta\omega_n e^{-\zeta\omega_n t}) \\ &+ e^{-\zeta\omega_n t} (\omega_d B \cos(\omega_d t)) + B \sin(\omega_d t) e^{-\zeta\omega_n t} \end{aligned}$$

$$\dot{x}(t=0) = A(1)(-\zeta\omega_n(1)) + (1)\omega_d B(1) \implies B = \frac{v_0 + \zeta\omega_n x_0}{\omega_d}$$

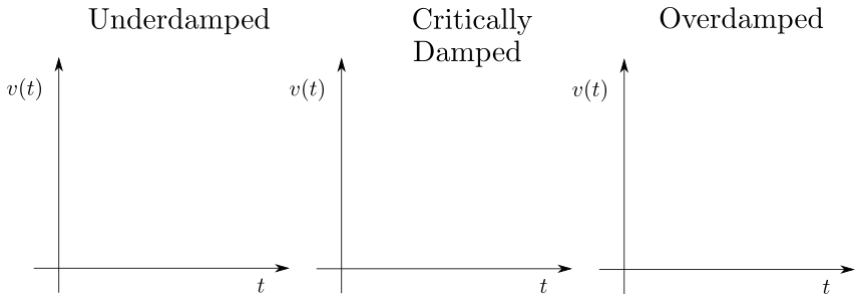
Finally we get to the response equation.

$$x(t) = e^{-\zeta\omega_n t} \left\{ x_0 \cos(\omega_d t) + \frac{v_0 + \zeta\omega_n x_0}{\omega_d} \sin(\omega_d t) \right\}$$

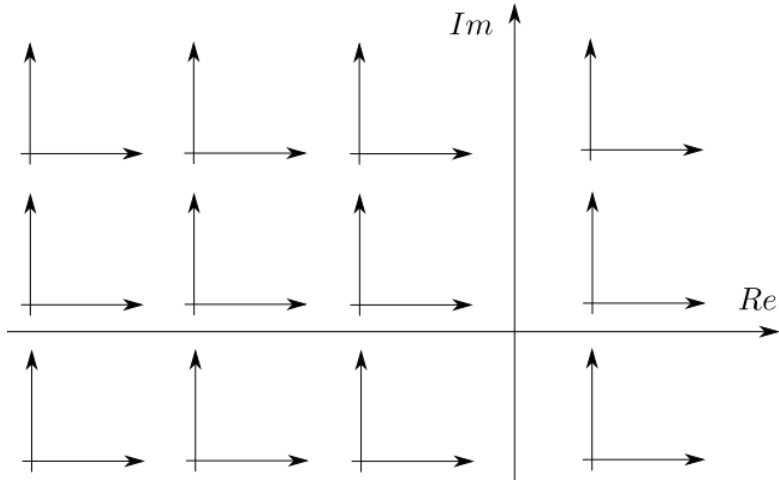


## Response of the Three Different Cases

Each of the three cases behaves in a *characteristic* way.



# Affects of Damping Ratio and Damped Natural Frequency



## References

- System Dynamics, Palm III, Third Edition - Section 8.2 - Response of Second Order Systems - pg. 484