ME242 – MECHANICAL ENGINEERING SYSTEMS

LECTURE 1

Class Guidelines

ME242 – MECHANICAL ENGINEERING SYSTEMS

Time/Place: Room 208, Packard Lab
Session 1: M/W/F 10:10-11:00
Session 2: M/W/F 11:10-12:00

Instructor: Eugenio Schuster,
Office: Room 550D, Packard Lab,
Email: schuster@lehigh.edu,
Office hours: Wednesday 6-8PM

Webpage: http://www.lehigh.edu/~eus204/Teaching/ME242/ME242.html

E-mail list: Make sure to be in the mailing list!!!

Book: "Engineering System Dynamics-A Unified Graph-Centered Approach" by Forbes T. Brown, Marcel Dekker, 2001 (ISBN: 0-8247-0616-1). Available at the Bookstore. We will cover partially Chapters 1 to 7.

Grader: Bryce VanArsdalen

ME242 – MECHANICAL ENGINEERING SYSTEMS

Prerequisites: MECH102, MAT205, and previously or concurrently, ME231

MATH 205. Linear Methods
Linear differential equations and applications; matrices and systems of linear equations; vector spaces; eigenvalues and application to linear systems of differential equations.

MECH 102. Dynamics
Particle dynamics, work-energy, impulse-momentum, impact, systems of particles; kinematics of rigid bodies, kinetics of rigid bodies in plane motion, energy, momentum, eccentric impact.

ME 231. Fluid Mechanics
Kinematics of fluid flow and similarity concepts. Equations of incompressible fluid flow with inviscid and viscous applications. Turbulence. One-dimensional compressible flow, shock waves. Boundary layers, separation, wakes and drag.

I will help you as we go by doing examples
which should refresh your memory

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Grading:

Homework/Projects	20%
In-class Test 1	20%
In-class Test 2	20%
Final	40%

Score	Letter Grade
92-100	A
90-91	A-
87-89	B+
82-86	B
80-81	B-
77-79	C+
72-76	C
70-71	C-
67-69	D+
62-66	D
60-61	D-
0-59	F

- A total of 100 points will be awarded as Numerical Grade
- A 100 Score corresponds to the top Numerical Grade of the class
- The students will be able to know their letter grades during the course computing their Scores based on their Numerical Grade as follows:

Score = Scale Factor x Numerical Grade

- The Scale Factor will be computed by the instructor and posted in the web-page.

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Policies:

- There are **NO** make-up tests or assignments
- Procedures for the conduct of exams will be explicitly stated before the exams
- Assignments and exams must be your **own work!**
- Homework is due at the **beginning** of class on the due date
- **NOT ALL** the problems will be graded
- Grading problems → Grader → Instructor
- Solutions of **ALL** the problems on the web site
- Solutions have to be comprehensible to be marked highly
- Follow the Homework Guidelines posted in the web page

Engineering Design Process

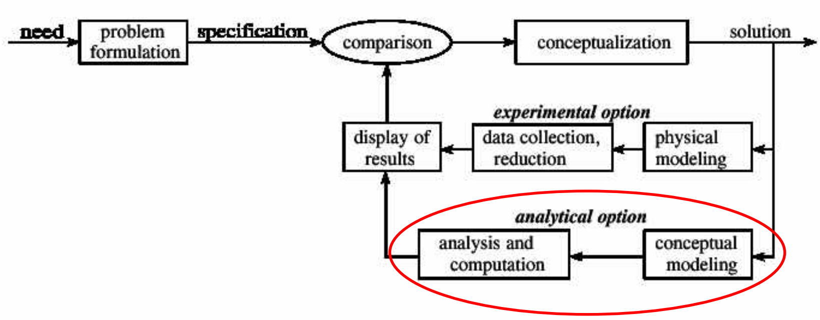
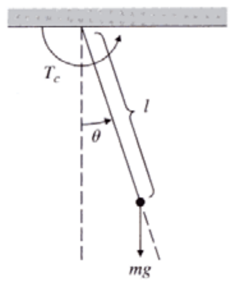


Figure 1.1: The engineering design process

Problem Formulation

Stabilization of Inverted Pendulum



MECHANICAL SYSTEMS

↓ MODELING

MATHEMATICAL REPRESENTATION OF THE MECHANICAL SYSTEM

DYNAMIC MODEL

(first step in this design process)

MODELING: Modeling of mechanical / vibrational / electrical / thermal / fluid systems using lumped-parameter models via unified approach

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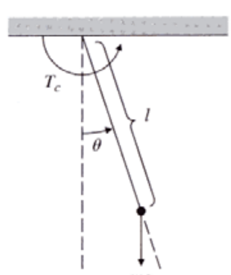
Bond-Graphs

Dynamic Model

MECHANICAL SYSTEM:

$$M = I\alpha$$ Newton's law



damping coefficient (b)

$$I\alpha = -lmg\sin\theta - b\omega + T_c$$

$$\omega = \dot{\theta}$$ angular velocity

$$\alpha = \dot{\omega} = \ddot{\theta}$$ angular acceleration

$$I = ml^2$$ moment of inertia

$$\ddot{\theta} = -\frac{b}{ml^2}\dot{\theta} - \frac{g}{l}\sin\theta + \frac{T_c}{ml^2}$$

Dynamic Model

DYNAMIC MODEL

↕

DIFFERENTIAL EQUATIONS

$$\ddot{\theta} = -\frac{b}{ml^2}\dot{\theta} - \frac{g}{l}\sin\theta + \frac{T_c}{ml^2}$$

ORDINARY DIFFERENTIAL EQUATIONS

- Linear → Analytical Solutions
- Nonlinear → Numerical Methods / Simulation
  - ↓ Matlab Simulink

Open loop simulations: pend_par.m, pendol01.mdl

Equilibrium and Linearization

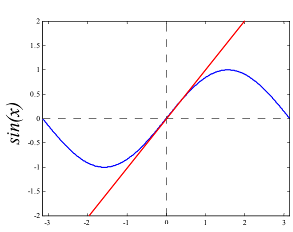
Which are the equilibrium points when T_c=0?

At equilibrium: $$\ddot{\theta} = \dot{\theta} = 0 \Rightarrow 0 = -\frac{g}{l}\sin\theta \Rightarrow \theta = 0, \pi$$

Stable ($\theta = 0$), Unstable ($\theta = \pi$)

What happens around $\theta=\pi$?

$$\theta = \pi + x \Rightarrow \ddot{x} = -\frac{b}{ml^2}\dot{x} - \frac{g}{l}\sin(\pi + x) + \frac{T_c}{ml^2} \Rightarrow \ddot{x} = -\frac{b}{ml^2}\dot{x} + \frac{g}{l}\sin(x) + \frac{T_c}{ml^2}$$



By Taylor Expansion:

$$\sin(x) = x + h.o.t. \Rightarrow \sin(x) \approx x$$

Linearized Equation:

$$\ddot{x} = -\frac{b}{ml^2}\dot{x} + \frac{g}{l}x + \frac{T_c}{ml^2}$$

Equilibrium Definition and Linearization → Analysis Simplification!!!

Analysis

$T_c = 0 \Rightarrow \ddot{x} + \frac{b}{ml^2}\dot{x} - \frac{g}{l}x = 0$ What is the solution *x(t)*?

Characteristic Equation

$$\lambda^2 + \frac{b}{ml^2}\lambda - \frac{g}{l} = 0 \Rightarrow \lambda_{1,2} = \frac{-\frac{b}{ml^2} \pm \sqrt{\left(\frac{b}{ml^2}\right)^2 + 4\frac{g}{l}}}{2}$$

$$x(t) = Ae^{\lambda_1 t} + Be^{\lambda_2 t}$$

The dynamics of the system is given by λ_1 and λ_2

real(λ_1, λ_2)>0 $\Rightarrow$ INSTABILITY

Stability Analysis

Model Representation

$\ddot{x} = -\frac{b}{ml^2}\dot{x} + \frac{g}{l}x + \frac{T_c}{ml^2}$ ⇨ Reduce to first order equations:

State Variable Representation

$$x_1 = x, \quad x_2 = \dot{x} \Rightarrow \begin{array}{l} \dot{x}_1 = x_2 \\ \dot{x}_2 = -\frac{b}{ml^2}x_2 + \frac{g}{l}x_1 + \frac{T_c}{ml^2} \end{array}$$

$$x \equiv \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}, u \equiv T_c \Rightarrow \dot{x} = \begin{bmatrix} 0 & 1 \\ \frac{g}{l} & -\frac{b}{ml^2} \end{bmatrix} x + \begin{bmatrix} 0 \\ \frac{1}{ml^2} \end{bmatrix} u = Ax + Bu$$

Model Representation → State Variables / Transfer Function

$eig(A) = \{\lambda : |\lambda I - A| = 0\} = \left\{\lambda : \lambda^2 + \frac{b}{ml^2}\lambda - \frac{g}{l} = 0\right\}$ Characteristic Equation

The dynamics of the system is given by the eigenvalues of the system matrix

Solution to the problem

$$\dot{x} = \begin{bmatrix} 0 & 1 \\ \frac{g}{l} & -\frac{b}{ml^2} \end{bmatrix} x + \begin{bmatrix} 0 \\ \frac{1}{ml^2} \end{bmatrix} u = Ax + Bu$$

$$u = -Kx = -[K_1 \quad K_2]x$$ Feedback Control

$$\dot{x} = (A - BK)x = \begin{bmatrix} 0 & 1 \\ \frac{g}{l} - \frac{1}{ml^2}K_1 & -\frac{b}{ml^2} - \frac{1}{ml^2}K_2 \end{bmatrix}$$

We choose K_1 and K_2 to make real(eig(A-BK))<0

Closed loop simulations: pend_par.m, statevar_control_lin.m pendcllin01.mdl

ME242 – MECHANICAL ENGINEERING SYSTEMS

Topics covered:

- Modeling of mechanical/vibrational/electrical/thermal/fluid systems using lumped-parameter models via bondgraphs
- Analytical solution of linear ordinary differential equations (ODE)
- Laplace Transform/Transfer Function representation
- Analytical solution of linear ODE via Laplace Transform
- State Variable representation
- Analytical solution of linear ODE via Matrix Exponential
- Nonlinear ordinary differential equations (ODE)
- Equilibrium/Linearization/Linearity
- Stability assessment based on eigenvalue analysis
- Phase plane analysis for second order systems
- Numerical methods for ordinary differential equations
- Simulation of dynamic systems: Matlab & Simulink
- Mode analysis for vibrational systems
- Frequency response
- Fourier Analysis