Control, Vibration, and Design of Dynamic Systems (ME161/ME261)

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Office location	113 Peterson (Bldg. 550), 416 Escondido Mall, Stanford CA 94305-4021		
Class location/time	Bldg 530 Room 127	Tues/Thurs 2:15-3:45	
Lab location/time	TBD	Sign up	Peterson 108
Web site	https://coursework.stanford.edu (Webmaster: **Helen Lu**) Old: www.stanford.edu/class/me161		
Holidays	Saturday Nov. 20 - Sunday Nov. 27, 2011		
Course reader	Distributed in class, $95		

Course description and prerequisites

Modeling, analysis, and measurement of mechanical and electromechanical systems. Numerical and analytical solutions of linear/nonlinear algebraic and ordinary differential equations governing the behavior of single and multiple degree of freedom systems. Stability, resonance, amplification, and control system design. Demonstrations and laboratory examples. Requires familiarity with dynamics, differential equations, linear algebra, and basic electronics.

Course objectives

Dynamic Systems is a prerequisite for ENGR105/ME105 (feedback control design), ME227 (vehicle dynamics), and is useful for ME281 (biomechanics of human movement) AA242/ME331 (advanced dynamics) and ME309 (finite element analysis). The course objectives are to:

- Model, introduce mathematical identifiers, analyze, and interpret dynamic systems
- Employ analytical and numerical methods to investigate real physical systems
- Gain insights into basic principles and feedback control with physical demonstrations, laboratories, and computer experiments (e.g., **M**otion**G**enesis, MATLAB®, and Working Model)
- Develop intuition about the time-dependent nature of dynamic systems
- Develop a hands-on, minds-on, can-do attitude

ABET (Accreditation Board of Engineering & Technology) outcomes – in order of relevance

- Ability to identify, formulate, and solve engineering problems
- Ability to use the techniques, skills, and modern engineering tools necessary for engineering practice
- Ability to apply knowledge of mathematics, science, and engineering
- Ability to design and conduct experiments, as well as to analyze and interpret data
- Ability to design a system, component, or process to meet desired needs

Topics covered

History of math & mechanics	Computational tools and ODEs	Computation & algebraic equations
Math review	Investigating $e^{p\,t}$	Classification of ODEs
Numerical solution of ODEs	Analytical solution of 1^{st}-order ODEs	Analytical solution of 2^{nd}-order ODEs
Root and root locus	Newton/Euler laws of 3D motion	Power/energy-rate principle
Harmonic forcing	Inhomogeneous 1^{st} and 2^{nd}-order ODEs	Motors, sensors, and circuits
Complex numbers	Laplace transforms	PID control
Linearization and stability	Linear algebra review	Eigenanalysis and coupled ODEs
State-space and coupled ODEs	State-space and PID control	System identification laboratories

[5] Paul prefers meeting students in office hours, scheduling a weekend or evening appointment, or talking on the telephone rather than corresponding by e-mail (particularly on technical matters).

Office hours (start Sunday September 26)

Day	Time	Location	Instructor
Sun	6:30 - 9:00$^+$	Bldg. 550 (Peterson) 126/Atrium	Kaushik Mani
Mon	4:00 - 6:45$^+$	Bldg. 550 (Peterson) 126/Atrium	Helen Lu
Mon	7:00 - 9:15$^+$	Bldg. 550 (Peterson) 162/Atrium	Eric Younge and Betai Koffi
Tues[a]	3:45 - 4:00$^+$	Bldg. 530 127 classroom	All
Tues	4:15 - 5:30$^+$	Bldg. 550 (Peterson) 126/Atrium	Paul Mitiguy or Betai (shared with E15)
Thurs[a]	3:45 - 4:00$^+$	Bldg. 530 127 classroom	Kaushik and Eric
Thurs	4:15 - 5:30$^+$	Bldg. 550 (Peterson) 126/Atrium	Paul Mitiguy or Betai (shared with E15)

Note: Instructor meeting and/or student appointments (as needed) Wednesday 8:00-9:30 in Peterson 126.
Note: It is hoped that CAs help bring demo equipment to/from class and clear board before/during/after lectures.
Note: Students are expected to help each other during office hours.
[a] Penalty-free "***grace-period***" office hours immediately after class are for students who attend class, put their assignments in the **box** before class, and leave blanks on their assignment for short unfinished questions.

Lab sessions

Day	Time	Group	Instructor
Thursday	4:00-6:00	A	Helen Lu & Betai Koffi
Thursday	6:00-8:00	B	Helen Lu & Eric Younge
Friday	11:00-1:00	C	Helen Lu & Kaushik Mani
Friday	1:00-3:00	D	Kaushik Mani & Betai Koffi
Friday	3:00-5:00	E	Eric Younge
Monday	4:00-6:00	F	Eric Younge
Tuesday	8:15-9:30 a.m.	G	Kaushik Mani

Grading

- **Graded material:** Student → **Box** → Kaushik Mani (alphabetize) → Graders (Vikas Agrawal,Lorenzo Limonta) → Kaushik Mani (Coursework/Excel) → Kaushik Mani (Photocopy, ABET) → Student (in class).

  Kaushik Mani is the grader intermediary. Consult **Kaushik** for questions about homework/test scores. Verify your scores at https://coursework.stanford.edu ***each week*** to ensure no grades were overlooked.

  When **you** choose to use computational tools (e.g., **M**otion**G**enesis, MATLAB®, C, etc.) to **avoid tedious calculations**, make sure **you** know what the computer is doing (it is not magic). Print out and submit the appropriate computational files (e.g., `.all` files) and include both input and ***output***.

- **Homework: 25%** Homework is graded with $\surd^{++}$ (100), $\surd^{+}$ (93), $\surd$ (85), $\surd^{-}$ (78), $\surd^{--}$ (70), or no credit (0). and is due **in the box** at the **start** of class.

  – Homework is only accepted **in the box** at the front of class (not by instructors or under office doors)
  – Homework passed in one lecture day late is penalized **15 points**. Homework passed in two lecture days late is penalized **35$^+$ points**, and is not thoroughly examined. Homework passed in more than two lecture days is penalized **55$^+$ points** and is not thoroughly examined.
  – Homework is not accepted after the last day of class.
  – To accommodate ill or overtired students, or students who need an extension for ***any*** other reason, ***one class*** homework extensions are permitted during the quarter. For example, a homework due Tuesday may be passed in on Thursday without penalty.
  – Submit your work and answers on separate sheets of paper (not on homework assignments).
  – Communicate clearly, write neatly, and use only one side of the paper.
  – Homework must be **stapled** (not paper clipped, dog-eared, origami, or bubble-gummed)

  Homework solutions are not posted. Ask your friends and instructors for help. Homework is practice, not a trade secret, and you are ***encouraged*** to work with your classmates and instructors. There is a strong correlation between high homework scores and high exam scores - and few reasons to do poorly on homework.

- **Laboratory: 15%** Each of the three parts of the lab is graded with a $\surd^{++}$, $\surd^{+}$, $\surd$, $\surd^{-}$, $\surd^{--}$, or 0 and is due **in the box** at the **start** of class. Some pre-lab questions are included (and submitted) with homework. Submit post-lab **separate** from homework. Staple and **submit Working Model pre-lab questions with the post-lab.**
  - 4% **Pre-lab**: Completing pre-lab questions before the lab session
  - 5% **Lab**: Participation in your ***regularly*** scheduled lab session
  - 6% **Post-lab**: On-time completion of post-lab questions.

  Labs are conducted in groups of 3 students, depending on class size. Each lab session is less than 2 hours and has at most 4 groups. Some labs may be done in class. Lab write-up consists of writing short answers to a few questions. The labs are intended to be ***fun***. We hope you enjoy getting an intuitive feel for dynamic systems and concepts learned in class.
- **Midterm: 25%** The midterm exam is in-class, open-book, and open-note. No calculators, computers, cell phones, or other electronic devices are allowed. **No makeup exam** is given.
- **Final: 35%** The final exam is in-class, open-book, and open-note. No calculators, computers, cell phones, or other electronic devices are allowed. The final exam covers the entire course (both before and after the midterm). No makeup exam will be given without university authorization.

Class participation, music, and video

Class participation is facilitated by **Eric Younge** and the instructor team who will call on students to participate in demos, answer questions, and work out problems on the board. Pre-class and half-time music and videos are played by **Betai Koffi** (send him music and video/YouTube requests).

Computer facilities

Computational tools (e.g., **M**otion**G**enesis, MATLAB®, C, ...) are useful for **generating** and/or **solving** equilibrium equations. Plotting capabilities in **MG**Plot, MATLAB® or Excel are useful for generating graphs. Instructions for obtaining student PC (Windows) and MAC (OSX) versions of **M**otion**G**enesis are available on the class website. Instructions for using these computer programs will be distributed in class. The software Working Model may be used in experiments.

Learning by design - we appreciate your feedback.

The word ***educate*** is from the Latin ***educare*** - "to draw out" (not "to stuff in"). Please provide suggestions, comments, criticism, ideas, content, images, video, and creative brainstorming about lectures, labs, homeworks, classroom interaction, office hours, software, hardware, etc. With 150^{+} classes of experience and a significant financial investment in your education, you are both learning experts and customers.

Course conduct and the Stanford University Honor Code and Fundamental Standard

Students are required to uphold Stanford University's Honor Code and Fundamental Standard. Makeup exams are not given without university authorization. Exam grades are non-negotiable and exams will not be regraded. Exams, homework, and other submitted material may be photo-copied by an instructor. Other than with an instructor, there is to be **no** class-related communication (no exchange of electronic devices, notes, homework, written material, or other information) during exams. Although you are ***encouraged*** to work with other students on homework, it is expected that each student pass in his/her own homework. Copying other students' homeworks is a violation of the Honor Code.

Students with documented disabilities

Students who may need an academic accommodation based on the impact of a disability must initiate the request with the Student Disability Resource Center (SDRC) located within the Office of Accessible Education (OAE) 563 Salvatierra Walk (phone: 723-1066). SDRC staff will evaluate the request with required documentation, recommend reasonable accommodations, and prepare an Accommodation Letter for faculty dated in the current quarter in which the request is being made. Students should contact the SDRC as soon as possible since timely notice is needed to coordinate accommodations.

Dynamic Systems Syllabus

Date	Who	Assignment	Topic
09/27 Tu	P	Hw 1 assigned Lab groups	Course introduction. What is a "dynamic system". **Demo: Babyboot**. **Class photos.** MIPSI problem solving methodology. Class road map in the context of ODEs. Math review: complex plane, logs, and trigonometry (circles, triangles, sine, cosine, amplitude-phase formula, and atan2 function).
09/29 Th	P		**Music/video: TBD.** Math review: differentiation, integration, the *good* product rule. Solutions of *first-order* ODEs by separation of variables and integration. Initial value problem for first-order ODE. Time constant. **Demo: Computer solution of nonlinear algebraic equations.**
Thurs-Mon	TAs	**Prelab due** **Go to lab**	**Motor spin-down test and first order response.** Experimentally determine the damping constants associated with a DC motor with dry Coulomb friction and/or viscous damping. **Hardware/software to be announced.**
10/04 Tu	P	**Hw 1 due** Hw 2,3 assigned	Classification of algebraic and differential equations. Knowing when to surrender to a computer. **Demo: Computer solution of nonlinear, inhomogeneous, ODEs for the babyboot.** This lecture brought to you by the letter e. The origins of e (e is for Euler, e is for engineer, e is for excellent). What is meant by "a solution to an ODE." Solutions of *first-order* and *second-order* ODEs by assumed solution.
10/06 Th	P	**Lab due**	Mathematical and physical significance of ζ, ω_n, ω_d, period of vibration, decay ratio, logarithmic decrement, rise time, peak time, overshoot, settling time, and picking related control constants. **Demo: Slinky with numbers, ruler, scale, and stop watch.**
Thurs-Mon	TAs	**Prelab due** **Go to lab**	See the effect of varying ω_n, ζ, mass, spring constant, damping constant, or initial deflection on a dynamic system. Notice that period is unaffected by the initial displacement! Measure the decay ratio, damping ratio, damping constant, period, ω_n, ω_d, overshoot, and settling time. Experimentally determine m, b, and k. **Slinky lab or other hardware.**
10/11 Tu	P	**Hw 2,3 due** Hw 16,17 assigned	Review of class road map. What is a mechanical engineer? Newton and thermodynamics. Design engineers and analysts. **Question of the day: Is the fundamental law of motion $\mathbf{F} = \frac{dm\mathbf{v}}{dt}$ or $\mathbf{F} = m\mathbf{a}$.** Aristotle and fundamental laws of *translational* motion: $\mathbf{F} = m\mathbf{v}$. **Demo: Nerf football**. Dissecting $\mathbf{F} = m\mathbf{a}$. Kinematics and vector review: dot-products, simple rotation matrices. The golden rule for vector differentiation. **Demo: Demonstrating the derivative of a vector with a bike pump.** Understanding translational and rotational kinematics via the inverted pendulum on a cart. Extending Newton's law to rigid bodies. Forces: Gravity, translational springs and dampers, and linear actuators (motors). **Demo: Bike pump as nonlinear spring/damper.** Springs in parallel and series. **Demo: Slinky.**

10/13 Th	P	**Lab due**	**Question of the day: What is the fundamental law of rotational motion?** Torques: rotational springs/dampers, DC motors. **Demo: Metronome, rotational spring.** Fundamental laws of 2D and 3D *rotational* motion: Euler $\mathbf{T} = I\boldsymbol{\alpha}$? **Discussion of e-mails from engineers at Loral/Lockheed. Demo: Spinning book. Demo: Spin stabilization with gyroscope. Demo: Rattleback.**
Thurs-Mon	TAs	**Prelab due** **Go to lab**	**Bifilar pendulum.** Experimental determination of mass, center of mass, and moment of inertia of a physical object.
10/18 Tu	P	**Hw 16,17 due** Hw 6 assigned	**Demo: Energy exchange for translational motion with slinky and person-particle.** Power/energy-rate method for one DOF problems. Gear problems. **Demo: Energy exchange for rotational motion with powerbee.** Equivalent systems. **Demo: Harmonic forcing slinky experiments.**
10/20 Th	P	**Lab due**	Solution and interpretation of 1st/2nd order, *inhomogeneous*, linear, constant-coefficient ODE. Harmonic forcing, resonance, the beat phenomenon. **Question of the day: Is resonance good?** Steady state amplitude and phase response to harmonic forcing. Real world application to whirl-flutter on XV22 Osprey. **Demo: Scotch-yoke/harmonic forcing. Demo: Harmonic forcing with an eccentric particle - earthquakes. Music Demo: DynamicSystemsSongCaltechNobelLaureateDavidPolitzer.mp3**
Thurs-Mon	TAs	**Prelab due** **Go to lab**	**Harmonic forcing.** Observe the effects of changing the mass m, damping constant b, spring constant k and forcing frequency Ω. **Hardware/software to be announced.** Alternate software/hardware lab: **Working Model: PID control of dynamic systems.**
10/23 Sun	H/B	**Review**	**Midterm exam review, 7:00-8:15.** Bldg. 550 (Peterson), room 200.
10/25 Tu	P	**Hw 6 due**	***Midterm exam*.** Room to be announced.
10/27 Th	P	**Lab due** Hw 7 assigned	Midterm solutions. Stability and interpretation of e^{pt} for real and/or complex values of p. Stability and roots to third and higher order ODE. Root locus.
Thurs-Mon	—	***No lab***	Halloween lab-vacation. Do not forget short homework due Tuesday!
11/01 Tu	P/K	**Hw 7 due** Hw 8 assigned	Basic electrical elements: resistors, capacitors and inductors and their measurement units. Parallel between electrical and mechanical elements? Torque motors and linear actuators as electrical elements (back-EMF and motor constants). Motor data sheets. Generating equations for electrical systems. Kirchoff current law. **Demo: Resistors, capacitors, inductors, motor with lamp.** Generators. **Demo: Generator radio and generator flashlight.** Sensors as electrical systems. **Demo: UFO Ball**. **Question of the day: Is God an EE, ChemE, ME, or CE? Question of the day: Is there a naturally occurring substance on Earth that is hotter than the sun's surface? Human sensors - how many fingers on back? Miracle ball - sensing human contact**

11/03 Th	P/H		Review of complex numbers. Engineering "proof" that all odd numbers are prime. Introduction to Laplace transforms. Converting an ODE in t (time) to an algebraic equation in s Laplace variable. Final value theorem and transfer functions. Generating rough sketches of time response using initial values, pole location, and the Final Value Theorem. Laplace transforms and steady state amplitude and phase response to harmonic forcing. **Demo: Working Model for MIPSI.**
Thurs-Mon	TAs	**Prelab due** **Go to lab**	**Digital high-pass and low-pass filters - Betai and Helen**. Hear and vary affect of low/high-pass filters on music. Design RC or LC circuits to create equivalent high-pass or low-pass filter.
11/08 Tu	P/B	**Hw 8 due** Hw 9 assigned	**Demo: MacScope demo of Fourier Series - amplitude vs. frequency for Soprano and Bass with good and raspy voices.** High-pass and low-pass electrical and mechanical devices. Understanding mechanical and electrical filters. **Demo of an electromechanical system: speakers and filters**. Simple RC circuits that act as high and low-pass filters of an audio signal.
11/10 Th	P	**Lab due**	Understanding PID control system design. Block diagrams. Picking PID control constants by root locus and pole placement. **Demo: P and PI cruise control of a car on a hill with wind. Demo: Feedback control.**
Thurs-Mon	TAs	**Prelab due**	**Fourier series/transform lab - Betai and Helen.** **MIPSI Assigned.** Ask and answer a sensible question for a dynamic system of your own choosing. Instructors will not help you solve your technical problem. Instructors help with your communication of your question/answer.
11/15 Tu	P	**Hw 9 due** Hw 10 assigned	**Demo: Simple particle pendulum.** Comparison of experimental and analytical results for small-angle approximation. **Demo: Car spinout.** Linearization of ODEs about a solution. **Demo: Rolling disk, Euler disk, Swinging Spring.**
11/17 Th	P/E	**Lab due**	Review of matrix algebra: Determinants, inverse, solving sets of linear equations, eigenvalues/eigenvectors. Solutions of 2nd order, undamped, **coupled**, homogeneous, linear, constant-coefficient, ODEs. **Go Stanford. Beat CAL.**
11/22 Tu 11/24 Th	— —	***Have fun*** ***Have fun***	Thanksgiving Holiday Thanksgiving Holiday
11/29 Tu	P	**Hw 10 due** Hw 12,13,14 assigned	Solutions of **coupled** undamped ODEs continued. Eigenvalues and eigenvectors. Initial values. **Demo: Rotor modes**. **Demo: Wilbur force pendulum. Demo Tarm's FEA Bell**.

12/01 Th	P	**Lab due**	Modal damping. State matrix solution of **damped coupled** ODEs. **Demo: Spinning book/condensed milk revisited. Demo: Two particle slinky with damping.** Life lesson on suffering. Inscribed in WWII death camp. "I believe in the sun, even when it's not shining. I believe in love, even when I can't feel it. ..." Quote from movie Princess Bride: "Life is pain. Anyone who tells you differently is selling something." Country-western song: "Love's the only house big enough for all the pain in this world." **Job talk**.
Thurs-Mon	TAs	**Prelab due** **Go to lab**	**Controlling dynamic systems.** Conceptual understanding of feedback control of multi-degree of freedom systems. **Working Model: Inverted pendulum on a cart**. **MIPSI due - or checkup with extension to last day of class.**
12/06 Tu	P	**WM Lab due**	State-space feedback control of multi-degree of freedom systems. **Demo: Student control of inverted pendula on a cart (pointer, ruler, broom-stick, croquet mallet with center of mass. Demo: Balancing Bear.**
12/08 Th	P	**Hw 12,13,14 due**	Course review. Course evaluations. Computer programs, e.g., **M**otion**G**enesis, MATLAB®, Working Model, and MSC.Adams, and their use in dynamic systems. **Class review:** Number line, algebra, trigonometry sine/cosine, amplitude-phase formulas, atan2, calculus (good product rule and fundamental theorem of calculus), behavior of e^{pt}, classification of algebraic and differential equations, uncoupled/coupled, linear/nonlinear, homogeneous/inhomogeneous, ... computer solution of linear/nonlinear algebraic equations, computer solution of linear/nonlinear ODEs, ODE solution via separation of variables and integration, ODE solution via assuming e^{pt}, damping constant, damping ratio, logarithmic decrement, decay ratio, undamped, underdamped, critically damped, overdamped, natural frequency, damped natural frequency, period of vibration, rise time, peak time, maximum overshoot, settling time root locus, stable, neutrally stable, unstable, kinematics (rotation matrices, angular velocity, golden rule of vector differentiation), dynamics (F=ma, M=dH/dt) Power/Energy-rate principle, Homogenous, particular, transient, and steady-state solutions, Harmonic forcing, resonance, motors, sensors, electrical circuits (voltage, current, resistors, inductors, capacitors, motor constants, back-EMF) complex numbers, complex algebra and exponentiation, Laplace transforms, transfer functions, sinusoidal transfer function, PID control of dynamic systems, Linearization (small angle approximations and Taylor series), Matrices and linear algebra (determinants, inverse, eigenvalues, eigenvectors), Undamped and damped coupled linear ODEs. State-space and control of multi-DOF systems. **Next classes:** E105 Controls; ME227 Vehicle Dynamics (Gerdes); ME281 Biomechanics of Human Movement (Delp); ME331B Advanced Dynamics (Mitiguy); ME309 FEA (Sheppard); CME200/ME300A Linear algebra; EE263 (Boyd). **Demo: Mode dance and physical significance of eigenvalues/vectors.**
12/11 Sun	E/K	**Review**	**Final exam review, 7:00-8:15**. Bldg. 550 (Peterson), room 200.
12/14 Wed	P	**Final exam**	***Final exam 7:00-10:00 p.m.*** (alternate 12:15-3:15 p.m.) Room to be announced.