Fall 2020

CEE 541. Structural Dynamics

Instructor: Henri P. Gavin, Rm. 162 Hudson Hall, henri.gavin@duke.edu
Class Time: Tu, Th, 8:30 – 9:45
Classroom: zoom 917 0479 3939
Text: Clough, R.W. and Penzien, J., *Dynamics of Structures* 3rd ed., Computers & Structures, 2003.
Paz, M. and Kim, Y.H., *Structural Dynamics: Theory and Computation* 6th ed., Springer 2019.
Course Website: http://www.duke.edu/~hpgavin/StructuralDynamics
Computers: Some assignments will involve MATLAB programming.
Office Hours: Mo 10:30-11:30 and We 11:00 - 12:30 at zoom 917 0479 3939
Academic Integrity: *The Duke Community Standard* applies.
Grading: Homework: 20%; Project: 30%; Midterm: 20%; Take-Home Final: 30%

BULLETIN DESCRIPTION

CEE 541. Structural Dynamics. Formulation of dynamic models for discrete and continuous structures; normal mode analysis, deterministic and stochastic responses to shocks and environmental loading (earthquakes, wind, and waves); introduction no nonlinear dynamic systems, analysis and stability of structural components (beams and cables and large systems such as offshore towers, moored ships, and floating platforms).

OUTLINE

1. **Equations of Motion.** d'Alembert's principle. principle of virtual displacements. generalized coordinates, Lagrange's equations, conservative and non-conservative forces, Hamilton's principle. Holonomic and nonholonomic constraints.

2. **Single Degree of Freedom Dynamics.** natural frequency, damping ratio, free response, impulse response, and harmonic response; log-decrement for light, moderate, and heavy viscous damping; Coulomb damping; eccentric mass excitation; vibration sensors; beats; Fourier series and fast Fourier transform.

3. **Convolution.** response to impulsive and transient loading; convolution in time and frequency domains, frequency domain filtering, shock spectra.

4. **Nonlinear Damping.** power-law, visco-elastic, and rate-independent (friction, complex-stiffness, bilinear, and hysteretic) damping models; equivalent linear stiffness and damping.

5. **Numerical Integration.** linear acceleration, Newmark-β, HHT-α, Runge-Kutta; iterative methods with application to inelastic systems. Elastic and inelastic response spectra.

6. **Structural Element Stiffness, Mass, and Damping Matrices.** (2D) bar element, Bernouli-Euler frame element, Timoshenko frame element, plane-stress and plane-strain 2D elements, and nonlinear cable element; elastic and geometric stiffness; consistent mass.

7. **Dynamics of Multiple Degree of Freedom Systems.** matrix assembly; general eigen-value problem; mode shapes; diagonalization; Rayleigh quotient; modal superposition; tuned mass dampers; Guyan reduction, dynamic condensation; Jacobi and subspace iteration.

8. **Classical and Non-classical Damping.** Rayleigh damping and Caughey damping matrices; non-diagonalizeable damping matrices, state-variables and complex modes; linear visco-elastic damping; linear time invariant system (LTI) analysis, free, harmonic, and transient response.

9. **Dynamics of Continuous Systems.** second order (string, bar, shaft, membrane) and fourth order (beam, plate) systems; wave, harmonic, and modal properties; simple boundary conditions and boundary conditions with concentrated mass and stiffness; Timoshenko beam, and Euler beam with axial effects; self-adjointness, orthogonality, and normal mode equations; approximate methods (Rayleigh-Ritz, assumed modes, Galerkin).

10. **Random Vibration.** random variables, random processes, power spectra, noise, extreme values, fatigue, estimation of power spectra from data, stochastic response for linear and nonlinear systems, upcrossing and first-passage statistics, application to wind, wave, and earthquake loading.

11. **Earthquake, Wind, and Wave Loading.** rigid-base excitation, ductility, response spectra, soil-structure interaction, bluff-body vortex shedding, galloping cables, fluid-structure interaction, slosh.

COURSE SCHEDULE (assignments subject to change)

Week	Dates	Topic	References
1.	8/17, 8/19	d'Alembert, virtual displacements, buckling	[6] 1, 8 [18] 21
		Experiment! cantilever beam-column	(1)
2.	8/25, 8/27	generalized coordinates, Lagrange's equations	[6] 16
	due 9/3	HW 1: Principle of Virtual Displacements and Lagrange's Eq'ns	(2)
3.	9/1, 9/3	Dynamics of Single Degree of Freedom Systems	[6] 2, 3, 4, 6.3
	due 9/10	HW 2: Simple Oscillators in the Time and Frequency Domain	[18]1,2,3.2-3.4,3.7-3.9,19.2,19.4
		Experiment! free response, resonance, sine sweeps & beats	(3a) (3b)
4.	9/8, 9/10	Convolution, Response Spectra, Nonlinear Damping	[6] pp 87-90, 5, 6.3, 3.7
	due 9/17	HW 3: Convolution and Response Spectra	[18]4.1-4.2, 5.1-5.3, 6.6
			(4a) (4b) (4c) (4d) (4e)
5.	9/15, 9/17	Numerical Integration	[6] 7 [18] 16.1, 16.5-16.6
	due 9/24	HW 4: Numerical Integration	(5)
6.	9/22, 9/24	Element Stiffness, Mass, and Damping Matrices	[6] 9, 10 [18] 14, 15, 9
	due 10/1	HW 5: structural elements and structural systems	(6a) (6b)
7.	9/29, 10/1	Dynamics of Multiple Degree of Freedom Systems	[6] 3.6, 11 [18] 7, 8
	due 10/8	HW 6: one-page project proposal	(7a) (7b) (7c) (7d)
		Experiment! modal analysis, tuned mass damper, base isolation	
8.	10/6, 10/8	non-classical damping and complex modes	(8a)
		Linear Time-Invariant (LTI) systems	(8b) (8c) (8d)
9.	10/13, 10/15	Dynamics of Continuous Systems	[6] 17, 18 [18] 17
		Strings, Bars, Shafts, Shear Beam (2nd order PDE)	
		Bernoulli-Euler Beams and Timoshenko Beams (4th order PDE)	
	due 10/29	HW 7: Distributed Parameter Systems	
10.	10/22, 10/22	Dynamics of Continuous Systems	[6] 18, 19
		Inner products, Self adjoint systems, Rayleigh-Ritz, Galerkin	
11.	10/27, 10/29	Random Vibration	[6] 20, 21, 22, 23 [18] 22
		Probability, Random Processes, Correlation, Power Spectral Density	
12.	11/3, 11/5	Random Vibration	scanned notes
		Simulation and Estimation, Response Statistics and Extremes	
	due 11/12	HW 8:	(11a)
13.	11/10, 11/12	Random Vibration	[6]24,25,26,27,28 [18]23,24,25
			(13)
14.	11/17, 11/19	reading period	
	11/24	project and take home final exam due	

COURSE REQUIREMENTS

- **The Duke Community Standard** http://www.integrity.duke.edu/standard.html: Duke University is a community dedicated to scholarship, leadership, and service and to the principles of honesty, fairness, respect, and accountability. Citizens of this community commit to reflect upon and uphold these principles in all academic and non-academic endeavors, and to protect and promote a culture of integrity.

  To uphold the Duke Community Standard:

  - I will not lie, cheat, or steal in my academic endeavors;
  - I will conduct myself honorably in all my endeavors; and
  - I will act if the Standard is compromised.

- **Short-term illness:** If you miss a due-date because you were sick, follow the university policy for submitting the missed assignment. http://trinity.duke.edu/academic-requirements?p=policy-short-term-illness-notification

- **Communication:** I use email for course announcements. There is no Sakai site for the course.

- **Due dates:** Homework due dates are shown in the course schedule.

- **Collaboration:** The Duke Community Standard applies to all work in the course, including homework problem sets. If you collaborate with another student, indicate your collaborator's name on each problem on which you collaborate.

- **Computer-Aided Solutions:** You may use software (such as MATLAB, Mathematica, and Maple) to help solve or simplify problems. If you do so, attach a printout of your own program/commands and results.

- **Homework grading:** Each homework assignment will be scored out of 100 points.

  Fifteen of the 100 points will be awarded for following the following rules on neatness:

  - Use pencil (so you can erase). A mechanical pencil is recommended.
  - Write neatly and clearly. Our TA's may lose patience with illegible solution sets.
  - Write your first and last name, the course number, the assignment number and the due-date in the upper right corner of the first page. Write the page number on each page (e.g., 3/6, means page 3 of 6)
  - Use a straight edge (a ruler or a triangle) to draw straight lines.
  - Present solutions to problems in the same order as listed in the assignment, and begin every problem on a new page unless the next solution is so short that it can fit on the same page.
  - Partial credit will be awarded *only* if the solution leading to an incorrect answer describes your thinking in words.
  - Draw a box around your final answer and provide the units of your answer (i.e., cm, psi).
  - Scan your hand-written solution set with a good PDF scanning app (I use one called Fast Scanner.) Email your solution to `hpgavin@duke.edu` *with the subject line:* `CEE 541: <your name> HW x` and name the `.pdf` file of your solution set: `CEE541-HWx-<YourName>.pdf`

- **Late work:** Grades for assignments submitted after the due-date will be penalized ten points for each day late; late penalties are not accrued for weekends or University holidays. Assignments submitted after graded assigments are returned receive no credit. Submit late work to me in person or under my office door.

References

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[2] Blevins, R.D., *Formulas for Natural Frequency and Mode Shape,* Van Nostrand, 1979.

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[7] Constantinou, M.C., Soong, T.T., and Dargush, G.F., *Passive Energy Dissipation Systems for Structural Design and Retrofit,* MCEER Monograph #1, 1998.

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[11] Hughes, T.J.R., Analysis of Transient Algorithms with Particular Reference to Stability Behavior. in *Computational Methods for Transient Analysis,* North-Holland, 1983, pp. 67–155.

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[19] Preumont, Andre, *Twelve Lectures on Structural Dynamics* Springer, 2013.

[20] Przemieniecki, J.S., *Theory of Matrix Structural Analysis,* Dover, 1985.

[21] Skinner, R. Ivan, Robinson, William H., and McVerry, Graeme H., *An Introduction to Seismic Isolation,* John Wiley & Sons, 1990

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[26] Sun, C.T. and Lu, Y.P., *Vibration Damping of Structural Elements,* Prentice-Hall, 1995.

[27] Tedesco, Joseph W., McDougal, William G., and Ross, C. Allen, *Structural Dynamics: Theory and Applications,* Addison-Wesley, 1999.

[28] Virgin, Lawrence N., *Introduction to Experimental Nonlinear Dynamics: A Case Study in Mechanical Vibration,* Cambridge, 2000.

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