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AE 326:
Vibrations and Structural Dynamics

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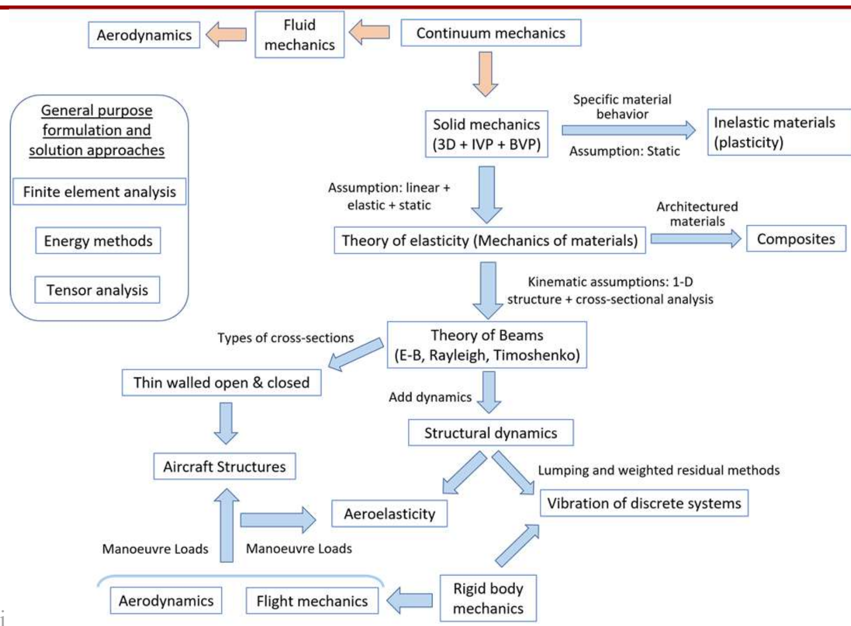
Roadmap of structures courses in the Aerospace department



Overview

Vibrations are back-and-forth or to-and-fro motions about a mean position

Why is a study of vibrations important?

- Vibrations and/or repetitive motion occur in numerous situations: electrical circuits, waves, optics, mechanics, etc. Mechanical vibrations are vibrations of entities that have physical mass, or inertia, as we shall see later.
- Vibrations are critical to the functioning of biological, aerospace, mechanical, and civil engineering systems.
- Vibrations may be desired due to operational requirement, or may arise due to unavoidable interactions between a structure and its environment.

Structural dynamics is the study of the time dependent behavior of mechanical engineering structures. It encompasses:

- Vibratory response (repetitive behavior)
- Transient response (non-repetitive behavior)
- Onset of instabilities and post-instability response (not covered in this course)

Practical relevance

Understanding and prediction of the vibratory response is critical in several engineering situations.

- Critical loading and maximum stress scenarios
- Dynamic instabilities
- Fatigue-based failure
- Estimating reduction or deterioration of performance in operational conditions
- Performance certification
- Maintenance scheduling
- Wear and tear assessment
- Energy harvesting
- Performance enhancement
- Vibration based flow control mechanisms

Examples of vibratory concerns in aeromechanical and civil structures

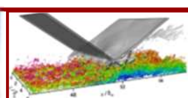
Base motion	Earthquake-based designs https://www.youtube.com/watch?v=xp2pGxFzrzI
Ground resonance	Coupling between rotor rotation, body rocking, and friction between the skid and ground. https://www.youtube.com/watch?v=-LFLV47VAbI
Aeroelasticity	Coupling between aerodynamic loads, wing and/or body and/or control surface. https://www.youtube.com/watch?v=HwHQF0159X8
Highly flexible aircraft	Coupling between flight dynamics, wing flexibility, and aerodynamic loads. https://www.youtube.com/watch?v=1NCOPLEJOl0
Propeller whirl	Coupling between propeller rotation and flexibility of the shaft https://www.youtube.com/watch?v=j6Q5ggtV-y8
Pogo effect in spacecraft	Coupling between engine surge and spacecraft vibration https://www.youtube.com/watch?v=pOOrXWLLza0

Repetitive motions are critical to functioning of biological creatures too!

Walking and running	https://www.youtube.com/watch?v=solNmc_Ijv4
Bird flapping	https://www.youtube.com/watch?v=1kztP_XTEPk
Insect hovering	https://www.youtube.com/watch?v=4Sgqb8wnQGA
	https://www.youtube.com/watch?v=lOrH0Gbt8YM
Snake locomotion	https://www.youtube.com/watch?v=7-AKPFiIEEw
Fish swimming	https://www.youtube.com/watch?v=I5Phg4q5EBU
Heart pumping	https://www.youtube.com/watch?v=ebzbKa32kuk

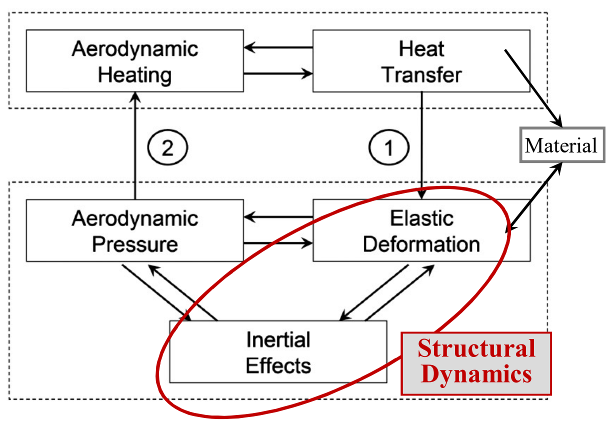
A complex design problem: Hypersonic aircraft

- Length in meters
- Mach 5-7
- ~ 100,000 feet altitude



Pirozzoli & Bernardini 2011

Courtesy of S. M. Spottswood, AFRL



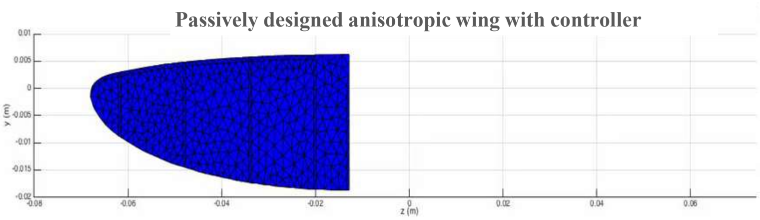
[*McNamara & Friedmann 2011*]

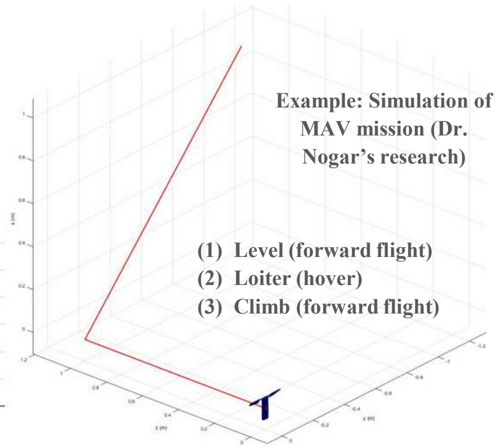
- Coupling between aerodynamic flow (heating & pressure), structural deformation, and potential material response.
- Structural concerns: thermal buckling and post-buckling vibrations, thermo-elastic and thermo-viscoplastic vibrations, etc.

A complex design problem: Bioinspired flyers

- Wings generate both propulsive and control forces
- Passively design for highly maneuverable flight
- Active design (morphing) for enhanced in-flight control

Thin, anisotropic, and highly flexible wings





Course Description

What to expect from the course

- Designed to be an introductory course on vibrations and structural dynamics
- We will discuss the 4 major steps in the analysis of structural dynamic systems
  - **Abstraction:** Reduce reality to an entity that can be modeled mathematically
  - **Formulation:** Determine the governing equations, and boundary and initial conditions
  - **Solution:** Solve the governing equations for given boundary and initial conditions
  - **Validation:** Check accuracy of mathematical model by comparing with truth model
- Emphasis is on formulation and solution strategies.
- Abstraction and validation may be required in specific assignments / quiz or exam questions

Goals:

- Understand the physics of vibrations using reduced order mathematical models.
- Tackle a range of structural dynamic problems using simple approaches.

Contents: Preliminaries and Background

- **Preliminaries**
  - Statics as a subset of dynamics
  - Analysis and abstraction of physical systems
  - Representation of kinematics using degrees of freedom
  - Concepts of discrete, distributed, and generalized coordinates

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- **Elements of Newtonian and analytical mechanics**
  - Newton's laws for particles
  - Concepts of inertia, momentum, and energy
  - D'Alembert's principle
  - Principle of virtual work
  - Concept of virtual displacements*
  - Euler-Lagrange equations*
  - The extended Hamilton principle*

Contents: Continuous to discrete systems

- **Equivalence of continuous and discrete systems**
  - The vibrating string problem
  - What are influence coefficients ?
  - Discretization of vibrating beams*
  - Discretization of shafts undergoing torsional vibrations*

Contents: Response of Single Degree of Freedom Systems

- **Initial conditions, i.e. no external excitation**
  - Undamped systems
  - Phase portraits
  - Types of damping; estimation techniques
  - Vibrations of damped systems
  - Numerical integration procedures

- **Forced response to external excitations**
  - Fourier series method for periodic excitations
  - Duhamel's integral approach for arbitrary excitations
  - Laplace transform approach for arbitrary excitations
  - Resonance
  - Estimation of damping
  - Applications: Base motions, beats, transmitted response, shock and vibration isolation

Contents: Two Degrees of Freedom Systems

- **Free and Forced Response**
  - Matrix formulation
  - Elastic and inertial coupling
  - Natural frequencies and mode shapes
  - Orthogonality of natural modes
  - Proportional and non-proportional cases of damping
  - Forced vibrations (modal analysis)
  - Beats, resonance, etc.
  - Introduction to aeroelasticity*
- **Comment on systems with n (> 2) DOFs**

Contents: Vibration of 1-D Continuous Systems*

- **Free and forced vibrations**
  - Governing equations and boundary conditions:
    - Transverse vibrations of strings
    - Flexural vibrations of beams
    - Longitudinal and torsional vibrations
  - Exact approaches
    - Natural frequencies and mode shapes
    - Admissible, comparison, and eigen-functions
    - Orthogonality conditions
    - Forced response (modal analysis)
  - Approximate approaches
    - Rayleigh quotient
    - Rayleigh-Ritz expansion and assumed modes method
    - Galerkin's method (weighted residual method)

- Primary focus of AE 715.
- Coverage in our course will depend on time available

Resources

- All communication through **Moodle**.
- **Offline lectures and tutorials**
- Slides / handwritten notes of select portions will be made available (posted on Moodle)
- Optional tutorial / problem-solving session will be arranged.

Recommended textbook: '*Mechanical vibrations*', by S. S. Rao, 6th Edition, 2018, Pearson, India.

Expected course coverage:

- Chapters 1 through 5
- Select portions of Chapters 6 through 9, and 11.

Note:

- I will not cover material in the same order as the book
- I may deviate or add material to topics from the book as I see fit.
- Strongly recommend you make notes.

Additional Resources

Books

1) '*Advanced Structural Dynamics*', by E. Kausel, Cambridge Univ. Press, 2017.
2) '*Vibration problems in Engineering*', by Weaver, Timoshenko, and Young, 5th Edition, Wiley, 1990.
3) '*Waves*', by Crawford, Berkeley Physics Series – Vol 3, McGraw-Hill, 1968.
4) *'Theory of Vibration with Applications*', by Thomson, 3rd edition, CBS publishers, 2002.
5) '*Dynamics of Structures*', by Clough and Penzien, 2003.
6) '*Dynamics of Structures*', by Humar, 3rd edition, 2012.
7) `*Elements of Vibration Analysis*' by Meirovitch, McGraw-Hill Education, 1986.
8) '*Introduction to Structural Dynamics*', by Biggs, 1964.
9) '*Vibrations and Waves*', by French, 1987.
10) '*Mechanical Vibration Practice with Basic Theory*', by Ramamurti, Narosa Publishing House, 2000.

Online resources:

1) Youtube lectures, NPTEL recordings
2) MIT open courseware and other freely available faculty notes

TAs and Office hours for the course

1) Anshuman Mehta
2) S. Ramkumar
3) K. Aditya

List will be updated once the TA list is finalized

- Discuss among yourselves and give me a slot for office hours.
- Slot has to be between 11:30 am and 5:30 pm on weekdays (excluding lecture hours).
- You can also reach me on Moodle or through my TAs if an appointment is required.

Evaluation (Tentative)

	Weight	Remarks
Quizzes (expect 2)	**20 %**	• Will be conducted during lecture hours. • Dates and material covered will be announced in advance. • One hand-written sheet will be allowed as an aid
Mid-term exam	**30 %**	• Will be held during the mid-term slot • One hand-written sheet will be allowed as an aid
End-term exam	**40 %**	• Will be held during the final exam slot • One hand-written sheet will be allowed as an aid
Assignments	**10%**	• Questions will be announced either in class or via Moodle