MECH 550Y 201: Fluid-Structure Interaction

Course Overview: The topic of fluid-structure interaction is quite vast and its applications are numerous in engineering problems ranging from solid rocket motor, aircraft wing and turbomachinery, tall bridges, nuclear plate assemblies, offshore platform/risers, subsea pipelines, paper printing to micro-aerial vehicle, parachutes, airbags, blood flow in arteries, heart valves, and among others. In particular, ocean and wind environments are full of coupled fluid-structure effects, which can have a significant impact on the dynamical performance of systems in offshore, aerospace, power transmission, hydrokinetic energy extraction. Understanding the impact of flow-induced loads on structural deformation and vibrations can lead to safer and cost-effective structures, especially for light and high-aspect-ratio structures with increased flexibility and harsh environmental conditions. Vortex-induced vibrations and fluttering of flexible foils are two common and fundamental canonical examples of these kinds of self-excited phenomena in cross-flow. Oscillating flexible cylinders or flapping of elastic foils in a freestream can form a great variety of vortex wake modes that can have a profound role in the performance of structural dynamics. This course is intended to provide comprehensive knowledge and overview of the underlying unsteady physics and coupled mechanical aspects of the fluid-structure interaction.

Rationale for introducing this module: Practicing mechanical engineers in aerospace, civil and marine/offshore industries must possess knowledge of fluid-structure interaction. Next generation aircraft, space vehicles, turbomachinery, offshore marine/systems and bridges need a detailed understanding of fluid-elastic effect and its implications on the design of flexible structures for high-performance, structural reliability and efficiency. The objectives of this course are to provide students with the fundamental understanding of fluid-elastic principles and concepts which are required to (i) enable physical insight into the behavior of a broad class of fluid-elastic instability; and (ii) to understand and model industrial strength coupled fluid-structure mechanics in a systematic and rigorous manner.

Course Coordinator: Rajeev Jaiman,
Office: CEME 2208F, Email: rjaiman@mech.ubc.ca

Prerequisites: Students should normally have taken an engineering or physics course in fluid and structural mechanics at the undergraduate level and be registered as graduate students.

Learning Objectives:

1. Familiarity with common types of coupled fluid-structure and aero/hydroelastic systems.
2. Identification of common non-dimensional numbers and coupled physical effects in fluid-structure systems.
3. Understanding of critical mathematical concepts and theories.
4. Working knowledge of vortex-induced vibration, galloping, limit cycle oscillations, flutter and other flow-induced vibration phenomena.
5. Overview of advanced computational techniques, reduced-order models and machine learning techniques.

Expected Outcomes:

- Understand the theoretical and mathematical aspects of fluid-structure interaction and aero/hydroelasticity
- Acquire the fundamental understanding of fluid-elastic instability for increasing complexity of phenomena such as divergence of lifting surface, limit cycle oscillation, flutter instability, buffeting and vortex-induced vibration
- Learn the concept of modal analysis, various methods of dynamical analysis of structures and simplified coupled fluid-elastic analysis
- Be able to perform preliminary design calculations to estimate the fluid-elastic instability, vortex-induced vibration, flutter limit for structures
- Be able to analyze and compute relevant critical parameters and the importance of incorporating fluid-elastic phenomena in engineering design and some elementary methods

Course Format and Evaluation

The students will meet twice weekly for 1½-2 hour lectures. These will be supplemented by a number of discussion sessions and student presentations.

Evaluation will comprise: Homework= 40%, Project= 30%, Final Exam= 30%
Based on the lectures, students will undertake a project to have hands-on experience of theory and analysis of fluid-structure interaction. A report on the project work will be prepared for evaluation.

Modes of Teaching and Learning:

Slides presentations; lectures and tutorials; out-of-lecture-hour consultations; course notes; computational demonstrations; relevant web-links; compulsory and supplementary reading list.

Lecture Topics and Organization:

1. **Introduction**
    a. Dimensional analysis
    b. Representative engineering problems
2. **Physical Concepts and Mathematical Formulation**
    a. Coupled oscillators
    b. Self-excited vibrations and synchronization
    c. General mathematical formulation
    d. Interface condition
3. **Basic Fluid and Structural Dynamics**
    a. Ideal potential flow
    b. Thin foil theory
    c. Unsteady force decomposition
    d. Single degree-of-freedom vibration theory
    e. Multi-degree-of freedom structures
    f. Modal structural analysis
    g. Examples: Cylinder flow, beam modal analysis
4. **Flapping of Streamline Bodies**
    a. Ideal fluid flow and thin structures
    b. Coupled analytical models
    c. Effects of non-dimensional parameters
    d. Computational analysis of flapping dynamics
    e. Examples: Thin filaments, paper flutter
5. **Vortex-Induced Vibration**
    a. Vortex wake behind a bluff body
    b. Unsteady forces and Strouhal number
    c. Coupling of wake and body motion
    d. Analytical models
    e. Computational analysis
    f. Examples: Marine risers and pipelines
6. **Galloping of Flexible Structures**
    a. Mechanism of galloping
    b. Galloping response
    c. Theoretical analysis
    d. Effects of vortex shedding and turbulence
    e. Effects of structural parameters
    f. Examples: Iced-up cables and bridges
7. **Static and Dynamic Aeroelasticity**
    a. Static divergence of wing
    b. Limit cycle oscillations
    c. Flutter analysis
8. **Coupled Fluid-Structure Systems**
    a. State-space time and frequency-domain formulations
    b. Reduced-order modeling
9. **Control of Fluid-Structure Interaction**
    a. Passive techniques

    b. Active methods
    c. Examples: VIV and flutter suppression devices

10. **Advanced Topics**
    a. Advanced fully-coupled analysis
    b. Nonlinear model order reduction
    c. Data-driven modeling and machine learning

Required Textbook:
None

Relevant books:

1. Blevins, R.D. 1990 Flow-induced vibration. Van Nostrand Reinhold, New York.
2. Paidoussis, M., Price, S. & de Langre, Emmanuel 2011 Fluid-structure interactions: cross-flow-induced instabilities. Cambridge University Press.
3. Dowell, E. H., A Modern Course on Aeroelasticity, Kluwer Academic Publishers, 1989
4. Y.C. Fung, An Introduction to the Theory of Aeroelasticity, Dover, 1994.

Journals:

1. Journals of Fluids and Structures
2. Journal of Sound and Vibration
3. Journal of Fluid Mechanics
4. AIAA Journal
5. Physics of Fluids
6. Journal of Wind Engineering and Industrial Aerodynamics
7. Journal of Fluids Engineering