Preliminary Examination Guidelines

I. Purpose of Exam
The Preliminary Exam establishes whether the Ph.D. Candidate has command of specified fundamental material in Applied Mathematics and one of five Topic Areas of mechanical and aerospace engineering. The Candidate must demonstrate capability to synthesize different elements of knowledge in the formulation and solution of open-ended problems and to exercise sound scientific scrutiny and judgment.

II. Format
The Preliminary Examination has two parts: Applied Mathematics and Topic Area. The Applied Mathematics examination is written; the Topic Area examination is oral. Each Candidate is required to take both parts. The Candidate must choose one of five available Topic Areas: Systems and Design, Dynamics and Controls, Fluid Dynamics, Solid Mechanics, or Thermal and Transport Sciences.

- **Applied Mathematics**: 150-minute written examination. See Appendix A for topics.
- **Topic Area**: 90-minute oral examination in one of the following subtopics:
  - Systems and Design.
  - Dynamics and Controls
  - Fluid Dynamics.
  - Solid Mechanics.
  - Thermal and Transport Sciences.

  Questions will be presented in writing to the student. See Appendices B – F for the topics in each Topic Area.

III. Preparation
The Preliminary Exam requires significant preparation. Good performance in classes alone does not guarantee good performance in the exam. Intensive and thorough review of the material, solving sample problems, and practice exam sessions with peers are highly recommended. The preliminary exam represents an excellent educational opportunity for the student to review and integrate undergraduate and graduate course material. In addition, it is very important that the Candidate practices and refines his/her presentation skills prior to the exam.
Attempting to take the exam without this level of preparation is not recommended.

IV. Schedule and Registration

The Preliminary Exam is offered in the Fall and Spring Quarters, at dates announced well in advance of the exam. Only students who have been formally admitted to the PhD program and have a PhD advisor on record are eligible to take the preliminary exam. All incoming graduate students who have been admitted to the PhD program and have previously received an MS degree must take the Preliminary Exam for the first time during the Fall Quarter of their second year in the program. If a second chance is required for the examination, it must be taken during the Spring Quarter of the second year. All incoming graduate students who have been admitted to the PhD program as MS/PhD students must take the Preliminary Exam for the first time in the Spring Quarter of their second year. If a second chance is required for the examination, it must be taken during the Fall Quarter of their third year. Students who do not take the Preliminary Exam in a timely fashion as defined above will not be considered to be in good academic standing and may not be allowed to continue in the Program.

The student together with the faculty advisor must petition for the Preliminary Exam at least six weeks prior to the start of the Exam period. Students should meet the requirements for “Demonstration of Oral English Proficiency for Teaching Assistant Employment” as described in the UCI Catalogue before petitioning for the Preliminary Exam. Petition forms are available at http://mae.eng.uci.edu/graduate/prelim_exam_form.pdf.

V. Examination Committees

The MAE Graduate Studies Committee chooses the Examiners, including exam chairs, for the five topical areas of the exam. At least four faculty members will constitute the examination committee for the Applied Math part. Three Examiners will be present during the Topic Area exam. The Candidate’s faculty advisor should not be involved in any part of the exam.

VI. Grading

Each of the Examination parts will receive a separate pass or fail grade from the responsible faculty team. Any part failed in the first taking must be retaken. If any part is failed twice, the Candidate has failed the Preliminary Examination and may not continue for the Ph.D. degree. Candidates must pass both parts of the examination.
Appendix A: Applied Mathematics Topics

Textbooks


Topics

A. Linear Algebra

2. Vectors spaces, linear independence, Wronskian, span and subspace, basis. G, Sections 9.6-9.9
3. Matrices: determinant, inverse, domain, range, null space, rank. G, Chapter 10
4. Eigenvalues and eigenvectors. G, Sections 11.1, 11.2
5. Basic properties, diagonalization. G, Sections 11.2, 11.4
6. Properties of symmetric (Hermitian) matrices, positive (semi) definite matrices, etc. G, Sections 11.3
7. Ax = b and the Least Squares Problem
8. Basic definition, existence and uniqueness (rank conditions). G, Chapter 8 and Section 10.5

B. Ordinary Differential Equations And Dynamical Systems

9. Phase plane and its use to study second order ODE. G, Sections 7.2, 7.3
10. Solution to general LTI systems: first order form (x' = Ax + Bu), Leibnitz rule, the solution to the first order form. C, Section 4.2
11. Decoupling, diagonalization and modal forms. G, Section 11.5
12. LTV systems, state transition matrices and their properties. C, Section 4.5 Stability
13. General definitions. C, Chapter 5
14. LTI: eigenvalues and the complete picture. C, Sections 5.2-5.4
15. LTV systems and eigenvalues. C, Section 5.5 Nonlinear Dynamical Systems
16. Phase Portrait. G, Section 7.2
17. Equilibrium points, stability, linearization about equilibrium points, use of eigenvalues for
stability of equilibrium points. G, Section 7.3
18. Duffing equation. G, Section 7.6 Solving ODE’s
22. Frobenius solution (regular singular point). G, Section 4.3

C. Partial Differential Equations

Appendix B: Systems and Design Topics

The Systems and Design Preliminary Exam is structured with two Parts as follows:

**Part I** – A 30-minute oral exam that will be taken by all students covering topics in Linear Systems and Optimization.

**Part II** – A 60-minute oral exam in which the student answers systems engineering and design questions in one of the following subtopic areas of his/her choice (chosen prior to the exam so that the appropriate examiners are present for the exam)

1. Robot Kinematics
3. Energy Systems

For both parts of the exam, the student will be presented with an engineering system or device and will be expected to model and analyze the system, in order to understand optimize its design. Note that students taking the exam a second time must take Part II in the same subtopic area, unless approval has been given by the MAE Graduate Advisor.

**Part I: Systems and Design - Design Using Linear Systems and Optimization**

Part I of the Systems and Design exam is a 30 minute exam that will test the ability to solve design problems based on the derivation and analysis of a system model and the optimization of its free parameters using linear systems and optimization techniques. Students will first be presented with a conceptual description of a mechanical system. They will then be expected to be able to derive (linear or linearized) equations of motion for the system, and to analyze those equations within a design framework.

**Topics**

1. Modeling of multi-degree of freedom, linear systems via Newton’s law or Lagrange’s equation, use of state space representations and transfer functions. Use of matrices to represent coordinate transformations, including rotation matrices and homogenous transformations (Relevant UCI Courses MAE 147, 200A, 241 and associated textbooks).

2. Analysis of the resulting model: natural frequencies and resonance, eigenvalues and eigenvectors, modes, stability, solution of the resulting differential equations (state transition matrix, matrix exponentials and their computation and properties). (Relevant UCI Courses: MAE 147, 200A, 241, 270)

3. Applying optimization techniques to the resulting models: optimization conditions for
unconstrained and constrained problems, their properties, and application to the models obtained (MAE 206)

Textbook resources

Greenwood, D.T. Principles of Dynamics, 2nd ed (Chapters 3,4,6)
   Linear System Theory and Design, 3rd ed. (Chapters 1 – 4)
Luenberger, D.G. and Ye, Y. Linear and Nonlinear Programming, 3rd edition (Chapters 1-11)
Thomson, T.T. Theory of Vibration with Applications, (Chapters 5-7)

PART II: Systems and Design - Robot Kinematics Topics

Textbooks


Topics

1. Rotation matrix, homogeneous transforms, Lie groups. Handbook 1; Craig 2; Tsai 2
2. Angular velocity, spatial velocity, Lie algebras. Handbook 1; Craig 5; Tsai 4, 5
3. Rotation axis and Screw axis, Cayley’s formula, matrix exponential. Handbook 1, Tsai 2
4. Force-Torque and Velocity-Angular velocity screws. Handbook 1, 3; Craig 5, Tsai 6
5. Derivation of kinematics equations. Handbook 1, 3; Craig 3, Tsai 2, 3
6. Solutions to direct and inverse kinematics. Craig 3, Tsai 2, 3
7. Jacobian and Virtual Work. Handbook 3; Craig 5, Tsai 6
8. Workspace and manipulability. Craig 1, 8; Tsai 1, 4, 5
PART II: Systems and Design - Micro-Electro-Mechanical Systems Topics

Textbooks


Topics

1. Fabrication Techniques (UV lithography[FMN v.2 Chs 1 and 2], dry etching [FMN v.2 Ch. 3] & [PMEMS Ch.1], properties/characteristics of single crystal Si [FMN v.1 Ch.4] & [PMEMS App.F], wet bulk micromachining [FMN v.2 Ch.4], PVD, CVD, and surface micromachining [FMN v.2 Chs 7 and 10] & [PMEMS Ch.1])

2. Principle of Sensing and Actuation (scaling laws [FMN v.3 Chs 1and 7] & [PMEMS Ch.14], fundamentals of capacitive/piezoelectric/thermal actuation [PMEMS Chs 15, 16, 17], fundamentals of piezoresistive/capacitive/piezoelectric sensing [PMEMS Chs 5,6,and 7], modeling microresonators [PMEMS Ch 20])

3. Foundations of metrology and characterization (conductivity measurements, capacitive measurements [PMEMS Ch 6, 8], profilometry, microscopy (Optical, SEM), Proximal Probes (STM, AFM) [all in FMN v.3 Ch.6], X-ray Analysis [FMN v.1 Ch. 2])

PART II: Systems and Design – Energy Systems Topics

Textbooks


Topics

1. Anode & cathode stoichiometry, fuel and oxidant utilization, thermal, atom, mass and energy
balances, exit partial pressure calculations, Nernst Potential (O’Hayre et al., Ch. 1, 2; Hamann et al., Ch. 1)

2. Electrochemical half reactions, electrochemical kinetics, charge carrier, charge, atom and mass balances (O’Hayre et al., Ch. 3; Hamann et al., Sec. 3.1, 4.1, 4.2)

3. Combustion stoichiometry, atom, mass, and energy balances, combustion thermochemistry (Turns, Ch. 1, 2)

4. Combustion mass transport, chemical kinetics, chemical mechanisms (Turns, Ch. 3, 4, 5)

5. Thermal management design, energy balances, pinch point analyses (O’Hayre et al., Sec. 10.1, 10.2, 10.3, 10.5, Ch. 12)

6. Physics of electricity, basic circuit analysis, AC power, integrated electrical grid network, power flow analysis, single- and three-phase power dynamics (von Meier, Ch. 1, 2, 3, 7)
Appendix C: Dynamics and Control Topics

**Kinematics and Dynamics** (Ref. 1, relevant course MAE 241)

- Particle kinematics and dynamics (Ch. 2, 3)
- Rigid body kinematics and dynamics (Ch. 7, 8)
- Rotation matrix and parametrizations. SO(3)
- Angular velocity
- Inertia matrix
- Newton-Euler equations
- Holonomic and nonholonomic constraints (Section 6-3)
- Lagrangian dynamics (Ch. 6)

**Dynamical Systems and Control** (relevant courses MAE 270A, 170)

- Benefits of feedback control (Ref. 2, Ch. 3)
- Linear control design using transfer functions via Root locus and Bode plots (Ref. 2, Ch. 4 and 5)
- Approximate linearization of nonlinear systems (Ref. 3, Ch. 2)
- Solution of $\dot{x} = Ax + Bu$ for linear time-invariant (LTI) and time-varying cases (Ref. 3, Ch. 4)
- Controllability and observability: definitions; tests for LTI system (Ref. 3, Ch. 6 and Ref. 5)
- Minimal state space realization for LTI system (Ref. 3, Ch. 7 and Ref. 5)
- Set point regulation via linear state feedback (Ref. 3, Ch. 8 and Ref. 5)
- Asymptotic tracking via linear state feedback (Ref. 3, Ch. 8 and Ref. 5)
- Observer design (Ref. 3, Ch. 8, and Ref. 5)

**Optimization** (Ref. 4, relevant course MAE 206)

- Theory
- Necessary and sufficient conditions for unconstrained minimization (Ch. 7)
- Necessary and sufficient conditions for constrained minimization (Ch. 11)
- Methods
- Steepest descent and Newton’s method (Ch. 8)
- Penalty method for constrained optimization (Ch. 13)

References:
2. Franklin, Powell, Emami-Naeini, Feedback Control of Dynamic Systems, Addison-Wesley, 1986 or equivalent undergraduate controls text.
Appendix D: Fluid Dynamics Topics

Textbooks


Topics

1. **Conservation laws and non-conservative forms.** Navier-Stokes equations, Euler equations, potential flow equations, including viscous potential flow. Nondimensional groupings of parameters, the incompressible limit, the inviscid limit. Energy and Entropy equations for both incompressible and compressible flows. K & C, Chapters 1, 2, 4; M-T, Chapters II, III.

2. **Use of non-primitive variables.** Kinematics, streamlines, planar and axisymmetric stream functions, velocity potential; key issues in vector calculus; generalized Bernoulli equation; vorticity dynamics; circulation, Kelvin's circulation theorem, Crocco's vorticity theorem; vortex lines, vortex tubes, vortex stretching; Kelvin’s minimum energy theorem. K & C 3, 4, 5; M-T I, IV, IX, XIII

3. **Use of complex variables.** Complex potential. Irrotational flows: sources, sinks, doublets, irrotational vortex; wedge flows, corner flows and stagnation point flows; flow past circular cylinders with and without circulation; lift force and Kutta- Joukowsky lift theorem. K & C 6; M-T V, VI, VII, VIII.

4. **Method of images.** Vortex-vortex interactions, vortex-wall interactions. K & C 6; M-T VIII, XIII.

5. **Mappings.** Joukowsky transformation, flows around plates and elliptical cylinders. 2D airfoils: lift and drag; Kutta condition; theorem of Schwarz and Christoffel, flows with steps, channel flows with area changes and branches. K & C 6, 15; M-T VI, X

6. **Free surface flows.** Impinging jets; flow through an orifice. M-T XI

7. **Flow stability.** Biot- Savart Law for vortical flows; vortex sheets; Linear perturbation analysis for hydrodynamic stability, Kelvin-Helmholtz instability, Rayleigh-Taylor flow, gravity waves, centrifugal instability; dispersion relations. K & C 7, 12; M-T XIII, XIV, XV.

8. **Water (gravity) waves.** Deep-water and shallow-water limits, group velocity. K & C 7; M-T XIV, XV.

9. **Axisymmetric potential flow around bodies of revolution.** K & C 6; M-T 6; XVI, XVII, XVI,
XVII.

10. **Viscosity.** Stress and strain tensors, Newtonian fluids and coefficient of viscosity; Navier-Stokes equations for heat-conducting, compressible fluid; nondimensional groupings of parameters. Boundary conditions. Diffusion of vorticity. W 1, 2, 2.


12. **Low-Reynolds-number flows.** Stokes flow, Oseen approximation; lubrication theory. W 3.

13. **Laminar boundary layers.** High-Reynolds-number flows over plates and wedges, Blasius and Falkner-Skan similar solutions, stagnation-point flow; integral methods, momentum and displacement thicknesses; axisymmetric flows. Boundary layers with suction and blowing. Compressible boundary layers: Crocco and Busemann integrals, Howarth and Dorodnitsin transformations. W 4, 7.


15. **Stability of laminar flows.** Linear theory of small disturbances, Orr-Sommerfeld equation and solutions; transition to turbulence. W 5.

16. **Turbulent flows.** Vorticity equation, vortex stretching; Concept of time-averaging, elementary statistics (mean, variance, correlation, spectrum), Reynolds-averaged Navier-Stokes equations (RANS), modeling of terms, derivation and explanation of the turbulent kinetic energy equation; turbulent pipe flow, law of the wall; turbulent boundary layer, mixing-length theory. W 6.

17. **One-dimensional steady flow.** Isentropic flow, area change and choked flow, friction, heat addition; normal shocks. Rayleigh and Fanno lines. L&R 2; S 5, 6.

18. **One-dimensional, unsteady flow.** Isentropic waves, travelling shocks, contact surface, shock-tube problem; method of characteristics, Riemann invariants; onedimensional and spherical acoustics. L&R 3; S 9.

19. **Two-dimensional compressible flow.** Oblique shocks; Prandtl-Meyer isentropic waves; method of characteristics, Riemann invariants; wave reflections and interactions. L&R 4; S 7, 9.

20. **Compressible potential flow.** Small perturbations in subsonic, transonic, and supersonic regimes, slender-body linearized supersonic aerodynamics, Prandtl- Glauert similarity rule; underexpanded and overexpanded flows through converging/ diverging nozzles (internal and external flow). L&R 8; S 8.

21. **Thermodynamic couplings.** The perfect gas law, physical significance of cp and cv, their dependence on molecular structure and temperature. K & C 1; W 7.

22. **Kinetic theory of gases.** Derivation of Navier-Stokes equations for monatomic gas; pressure forces at wall; use of Krook model to determine Newtonian relationship between viscous stress and strain. V & K 1, 2, 9.
23. **Elementary engineering flows.** Theoretical and practical knowledge of elementary engineering flows, from low to high Reynolds numbers: flow around cylinder, sphere, plate, airfoil, finite wing; orifice flow. K & C 9, 15; W 3, 4.
Appendix E: Solid Mechanics Topics

Textbooks


Topics


8. **Constitutive equations.** Elasticity: generalized Hooke’s law; isotropic elastic materials; symmetry considerations; relation among elastic properties. Plasticity: yield surface; flow rules for isotropic and kinematic hardening. *MM, Ch. 6. FT, Ch. 6.1-12.* Basic notions of viscoelasticity (Maxwell, Voigt and Kelvin models). *FT, Ch. 1.*


10. **Principle of virtual work.** *FT, Ch. 10.7.*

11. **Basic notions of the Finite Elements method.** One and two-dimensional problems with one-dimensional elements (e.g. frames). Shape functions. Assembling global matrices. *THGM, Ch. 6.7-6.8.*
Appendix F: Thermal and Transport Sciences Topics

Preliminary Exam Format and Instructions

Paper Presentation and Exam

• The student is asked to prepare for a 15-minutes presentation on a research paper, which will be selected by the committee and announced 2 weeks before the exam, with no more than 15 slides

• The presentation is expected to include the following as an example
  - Summary of approach and major findings
  - Critique and/or support of approach and major findings
  - Recommendations for future work or improvements

• The presentation will be interrupted by the committee, and the exam can last up to 80 minutes

• The examiners will ask questions on the paper and fundamentals of thermal/transport science

• For the fundamentals, study guide materials are provided in the next section

• The evaluation criteria will include the following aspects: Understanding of Paper, Critique of Work, Fundamental Questions, and Communication Skills

Preliminary Exam Study Guide Materials

Recommended Books


Related Topics

1. Basic concepts of thermodynamics: Energy, Forms of energy, Closed and open systems, Equilibrium and state, Thermodynamic properties of a system (U, V, m, T, P, etc.), Entropy and enthalpy, Reversible/irreversible processes, Energy storage modes (translation, vibration, rotation, and electron), Partition function and its relevance to the thermodynamic properties. MSB&B, Ch. 2-6.

2. Laws of thermodynamics and power systems: First/second/third law, First/second law analysis, Cycle analysis (e.g., Otto, Diesel, Brayton, and Rankine cycles...), Ideal/real refrigeration cycle,
Combustion process, Analysis of reacting systems. MSB&B, Ch. 8-10, 13.


4. Basic definitions and conservation of heat/mass transfer: Conduction, convection, and radiation, Fundamentals of mass transfer, Energy equation and special forms of the energy equation, Differential equations of mass transfer. IDB&L, Ch. 1.


6. Convection heat transfer: Forced vs. free convection, Laminar vs. turbulent flow, Internal vs. external flows, Dimensional analysis: characteristic quantities, dimensionless groups: Re, Pr, Ec, Nu, Gr, St, Order of magnitude scaling and negligible terms. IDB&L, Ch. 6-9.