DOCTOR OF PHILOSOPHY IN MECHANICAL ENGINEERING
STUDY PROCESS AND DEGREE REQUIREMENTS

This document outlines the sequence and details of the study process, and the requirements for the degree of Ph.D. in Mechanical Engineering. These guidelines complement the general university requirements as specified in the Graduate Catalog.

1. Qualifier Exam

The purpose of this exam is to ensure that all students admitted to the doctoral program have the background, training, and educational preparation necessary to accomplish all the requirements of the program. This is a written exam that is general in scope, requiring an application of core mechanical engineering principles in the student's overall area of specialization. The student must demonstrate a Masters' level understanding of the subject matter.

Students must take the exam for the first time within one year of registering in the Ph.D. program. The exam will be administered by faculty members nominated annually by the MAE faculty at the beginning of the academic year. The exam will be held during the third week of the fall, spring and summer I semesters. If any one of the examination dates coincides with a holiday, the exam will be postponed to the fourth week of the semester. Students planning on taking the exam should submit a request to the department Chairperson who will in turn ask the Department Graduate Curriculum Committee to schedule these exams. The student request must include specific choices of subject areas (listed below), according to the following deadlines:

- Fall August 1
- Spring December 1
- Summer I April 1

Each student must take the exam in Mathematics and two of the following six areas:

- Fluid Mechanics
- Thermodynamics/Heat Transfer
- Structural Mechanics
- Materials
- Control Systems
- Dynamics and Vibrations

A list of topics included in the above subject area exams are attached. Students will be allowed the use of background material in the form of textbooks and a maximum of ten pages of notes during these exams. Each subject exam will be four hours in duration. A student will not be required to take more than one subject exam per day. Faculty responsible for administering a specific subject area exam will evaluate and grade the performance of all students taking that exam as Satisfactory or Unsatisfactory. No *a priori* numerical percentage requirement will be established for these exams, but the students are expected to demonstrate adequate command of the subject through their answers to the specific questions on the exams. These exams do not carry any credit hours.

- A student who receives Satisfactory grades in each of the three areas will be considered to have passed the Qualifier Exam.
- A student who receives Usatisfactory grades in any of the three tested areas must repeat only the subject exams in which the Unsatisfactory grade(s) was received.
- A student taking all or part of the Qualifier Exam for the second time must receive Satisfactory grades on all parts taken to be allowed to continue in the Ph.D. program.
- No student may take the entire Qualifier Exam or any part thereof more than two times.

A student that has passed the requirements of the Qualifier Exam cited above will be considered officially admitted into the mechanical engineering doctoral program.

2. Mathematics Requirement

Competence in Mathematics is required not only to pass the qualifier exam, but also to complete coursework and perform the required level of research in the Ph.D. program. It is the responsibility of the student, with advice from the doctoral advisor to evaluate the student's level of competence in Mathematics, and establish additional preparation, if necessary, through supplemental coursework.

3. Coursework

At least thirty credit hours of coursework *beyond the Masters level* must be taken by a Ph.D. student. These courses must include 600 and 700 level graduate courses with the following restrictions and exceptions:

- Ph.D. credit will be given for MAE department 500 level courses only in the special circumstance that the specific course is a pre-requisite for 600 or 700 level courses subsequently taken by the student, or is required by the doctoral committee.
- Eighteen of the thirty hours of coursework must be 600 level or higher
- Eighteen of the thirty hours of coursework included for Ph.D. credit must be MAE department courses
- Ph.D. credit will be given for ME 695, only when it is specifically offered as a new course in preparation while the university-wide curriculum approval process is being completed
- ME 697 is not approved for Ph.D. credit
- Up to six hours of ME 710 (independent research) will be allowed as part of the thirty credit. The independent research conducted for ME 710 must be different than the dissertation topic being pursued by the student

4. Research Proposal and Specialty Exam

Immediately after passing the qualifier exam, the student should choose a Doctoral Research Committee consisting of four members of the Graduate Faculty, including the doctoral advisor and at least one member from outside the MAE department. The student is required to submit a detailed research proposal for evaluation by this committee. A specialty exam must then be taken for the evaluation of the depth acquired by the student in his/her area of interest, and to determine the adequacy of preparation toward dissertation research. (No credit hours will be assigned to the specialty exam.) The exam will be designed specifically for each student and administered by this committee near the end of the required course work. The student will be invited to orally defend the research proposal only if the written responses to the specialty exam are deemed satisfactory. This stage will be administered in the following steps:

1. The student submits a detailed research proposal to the committee that includes the background, literature review, objectives, and proposed research methodology for the dissertation research. Adequacy of the dissertation proposal will be determined on the basis of preparation, originality, scope and depth of the proposed work, proposed research methodology, anticipated difficulties in execution, and resources available to conduct the proposed work.

2. Within one month of submission of the proposal, the committee will collectively determine the adequacy of the proposal. If this proposal is considered substantially adequate for discussion with the student, a take-home exam will be prepared by the committee, consisting of four questions (one per committee member, including the doctoral advisor) that are related to the proposed dissertation work. The student will have up to one week to prepare written responses to these questions.

3. The committee will review and evaluate the written responses and proceed with one of the following courses of action:

a) If the committee deems both the student's proposed solutions to the specific problems and the dissertation proposal to be substantially satisfactory, an oral presentation of the dissertation proposal will be held. This presentation will be open to all interested faculty. At the conclusion of the presentation, a closed session will be held between the student and the committee, in which the student's answers to the specific questions are discussed, and the committee may make minor suggestions regarding the proposed dissertation research. No re-submission will be required. The student will then be considered to have passed the specialty exam, and will officially become a Ph.D. candidate in the department. A letter to this effect will be forwarded to the student, the MAE department Chair, and the Graduate College.

b) An oral presentation of the dissertation proposal will also be held if the committee identifies some deficiencies in the response to (a) the specific questions, and/or (b) the dissertation proposal, but considers the combined submissions to be adequate for further discussion. This presentation will be open to all interested faculty. At the conclusion of the presentation, a closed session will be held between the student and the committee, in which the student's answers to the specific questions are discussed, and the committee may recommend a submission of modified answers. In addition, modifications to the proposed dissertation research will be recommended, based on the above-mentioned criteria. The student will submit the revised response within two weeks of the oral presentation for a re-evaluation by the committee. If the re-submission is deemed acceptable by the committee, the student will be considered to have passed the specialty exam, and will officially become a Ph.D. candidate in the department. A letter to this effect will be forwarded to the student, the MAE department Chair, and the Graduate College.

c) If the response to the specific questions, and/or the dissertation proposal is deemed inadequate, a re-examination will be required at least one semester after the date of the first exam. Additional preparation, which might be comprised of coursework, independent research, and other appropriate measures, will also be recommended by the committee. This preparation must be accomplished before the exam is offered again. The re-examination will require a re-submission of the proposal and will also include specific questions from the committee members. The specialty exam may be taken up to a maximum of two times by any student.

Upon receipt of the letter indicating a change to Ph.D. candidate status, the student should form a Dissertation Committee, consisting of four members of the Graduate Faculty, including the doctoral advisor and at least one member from outside the MAE department.

5. Final Oral Exam (Dissertation Defense)

This will be conducted at the conclusion of the research, within one month after the submission of the dissertation to the dissertation committee with the approval of the committee. The first hour of the defense will be open to the public, and the second hour held in a closed session with the dissertation committee. The dissertation defense must be held within five years after the student has passed the specialty exam. If the defense is not held within this time, the student will be required to re-take the specialty exam. Based on the presentation of dissertation work, the committee will recommend required modifications to the dissertation that might include further research, revisions to the dissertation, and other measures, as appropriate (such as a second oral exam); or approval of the Ph.D. dissertation and award of the degree.

LIST OF TOPICS INCLUDED IN EACH SUBJECT AREA

MATHEMATICS

It is expected the a Ph.D. candidate has a working understanding of methods of solving ordinary and partial differential equations. The topics from which the mathematics area exam is composed are related to methods used to solve differential equations.

- closed form solution techniques for ordinary differential equations including the method of undetermined coefficients and Laplace transforms
- closed form solution techniques for partial differential equations including separation of variables and the method of characteristics
- series solutions for ordinary or partial differential equations including equations including power series, Bessell functions, Legendre polynomials, Frobenius series and Fourier series
- numerical methods for solving initial value and boundary value ordinary differential equations
- numerical methods for solving partial differential equations
- linear algebra as it is related to solving systems of differential equations including representing the system state space form, solving systems of equations, solving eigenvalue problems and determining determinants
- the manipulation of complex numbers and their applications in solving differential equations
- using variational calculus to derive a variational stationary principle for a differential equation or vise versa
- numerical methods for solving linear and nonlinear systems of equations and eigenvalue problems
- linearizing nonlinear equations
- approximate methods for solving differential equations including Rayleigh-Ritz and Weighted Residual methods

These topics are now typically covered in ME 560, ME 561, and ME 562

FLUID MECHANICS TOPICS

Objective: to evaluate the candidate's understanding of incompressible and compressible fluid mechanics as applied to aero/hydrodynamic design, and performance prediction.

Topics:

- basic laws of fluid mechanics, differential and integral forms, Reynolds' transport equation
- Navier-Stokes and Euler's equations, the effects of inertial, viscous, and body forces, some exact solutions
- Kinematics of fluid motion, vector and tensor representations, vorticity
- dimensional analysis, Buckingham's theorem
- potential flow, superposition of basic solutions, complex potential
- boundary layer equations, stability and transition
- compressible flow: isentropic flow, flows with friction and heat transfer, shock waves, linearized flow

Suggested readings:

Introduction to Fluid Mechanics, Fox and McDonald
for the fundamentals of fluid mechanics
, Panton, Karamcheti, Katz and Plotkin
Ideal flow, fluid kinematics, singularity solutions, dimensional analysis
, Schlichting and White
Navier-Stokes equation, Viscous flow, boundary layer concepts, introduction to turbulence
Compressible Fluid Flow, Liepman and Roshko
Compressible flow, normal and oblique shocks

THERMODYNAMICS/HEAT TRANSFER

Objective: To test the students' understanding of the fundamentals of steady state and transient conduction, forced and natural convection, radiation, and design of heat exchangers

Topics:
Conduction

Governing Equations: Steady Heat Conduction, Fourier's Law of Heat Conduction, Heat Conduction Equation, Boundary and Initial Conditions, Differential and Integral formulations

Solutions: Composite Wall, Resistance Network Concept, Contract Resistance, Conduction Across Cylindrical and Spherical Shells, Overall UA Concept, Conduction with Internal Energy Generation (Plane Wall and Cylindrical Systems), Finite-Difference Methods for 2-D Steady Conduction, Superposition Principle , Power Series Solutions (Bessel Functions), Boundary value problems, Separation of Variables, Multidimensional solutions in terms of 1-D solutions

Fins: General Conduction Analysis and Boundary Conditions for Different Cases, Fin Efficiency, Simplifications, Variable Cross-section fins, Surface Efficiency

Unsteady Conduction: Lumped Capacitance Method, Unsteady Conduction in a Plane Wall, Convective Cooling of Slabs, Cylinders, and Spheres, Temperature Response Charts (Heisler Charts), Semi-Infinite Solid, and Finite-Difference Methods for 1-D Unsteady Conduction

Forced Convection

Conservation Principles: Rate Equations, Equations of Continuity, Momentum, and Energy Transfer and Simplifications, Non-dimensionalizaton and Physical Significance of Parameters; One-Dimensional Solutions: Couette Flow, Poiseuille Flow

Laminar Flow in Ducts: Fully developed Laminar Flow in Circular and Noncircular Ducts, Bulk Temperature, Constant Surface Temperature and Constant Surface Heat Flux Condition, Developing Flow, Laminar Slug Flow in a Circular Duct, Hydrodynamically and Thermally Developing Flows, Reference Temperatures for Fluid Properties Evaluation, Temperature Dependent Properties

Laminar Boundary Layers: Boundary Layer Equations, Flow over a Flat Plate – Velocity and Temperature Distribution, Local and Average Heat Transfer Coefficients, Similarity Solutions

Turbulence: Laminar-to-Turbulent Transition, Time-Averaged Describing Equations, Universal Turbulent Velocity Profile; Turbulent Boundary Layers (flat plates, ducts, etc.); Empirical correlations; Thermal Entry Length

Natural Convection

Governing Equations, Physical Explanations, Laminar Natural Convection form a Constant-Temperature Vertical Plate in an Infinite Fluid – Exact and Approximate Solution, Boussinesq Approximation Turbulent Natural Convection from a Vertical Plate of a Constant Temperature, Empirical Relationships for Natural Convection: Vertical Plate, Horizontal Plate, Vertical Cylinder, Horizontal Cylinder, Enclosures, Combined Natural and Forced Convection

Thermal Radiation

The Physics of Radiation, Black Body Radiation Exchange between Surfaces, Shape factors, Resistance Network for Black Surfaces, Radiation Exchange Between Gray, Diffuse Surfaces, Re-radiating Surfaces, Spectral Characteristics of Surface Radiation (Planck's Law and Fractional Functions), Solar Radiation and Solar-Thermal Radiation Exchange

Heat Exchangers

Types of Heat Exchangers, Energy Balances, Overall Heat Transfer Coefficient and Fouling, Unfinned and Finned Heat Exchangers, Typical Temperature Profiles, Design Problem: UA-LMTD Method, Rating Problem: E-NTU Method, Crossflow Heat Exchangers, Heat Transfer Enhancement

Note: In addition to the above topics, the student will also be expected to have a strong background in basic thermodynamics.

Suggested Reading:

Basics:

Fundamentals of Heat Transfer, Incropera and Dewitt, 3rd Ed., Wiley, 1990
Basic Heat and Mass Transfer, Mils, Irwin, 1995
Introduction to Fluid Mechanics, Fox, and McDonald, 4th edition, Wiley, 1992

Conduction:

Conduction and Heat Transfer, Arpaci, Addisson Wesley, 1966
Conduction in Heat of Solids, Carslaw and Jaeger, Oxford: Clarendon Press, 1959
Heat Conduction, Kakac and Yener, 3rd Ed., Taylor and Francis, 1993
Heat Conduction and Mass Diffusion, Gebhart, McGraw Hill, 1993
Heat Conduction, Ozisik, 2nd Ed., Wiley 1993

Convection:

Convective Heat Transfer, Burmeister, 2nd edition, John Wiley and Sons, 1993
Convective Heat Transfer, Kakac and Yener, 2nd edition, CRC Press, Inc., 1995
Convective Heat and Mass Transfer, Kays, and Crawford, 3rd edition, McGraw-Hill, 1993
Convective Heat Transfer, Bejan, 2nd edition, John Wiley and Sons, 1995
Analysis of Heat and Mass Transfer, Eckert and Drake, Hemisphere, 1987
Boundary Layer Theory, Schlichting, 7th edition, McGraw-Hill, 1979
Viscous Fluid flow, White, 2nd edition, McGraw-Hill, 1991

Radiation:

Thermal Radiation Heat Transfer, Siegel and Howell, 2nd Ed., Hemisphere, 1981

STRUCTURAL MECHANICS

Topics:
Beams: bending of (nonsymmetric) beams, statically indeterminate beams, composite beams, torsion of circular cross-section beams, torsion of rectangular and elliptical cross-section beams, torsion of single cell thin-walled beam, shear center of thin-walled beam, shear-bending of thick-walled beams, bending of curved beams, plastic hinges, beam vibration

Flat Plates: kinematics, stress resultants, equilibrium, deflections of rectangular plates
3-D elasticity: equilibrium equations, strain-displacement relations, constitutive equations, compatibility equations, stress, (and strain) transformations; Principal stresses (and strains) and directions, plane stress, plane strain, Mohr circle, thermal stresses, principle of superposition

Structural Failure: yield theories, fracture mechanics, high cycle fatigue, column buckling (including geometric and material nonlinearities and post-buckling)

Energy and Variational Methods: principle of virtual work, principle of stationary total potential energy, Castigilano's theorem, Rayleigh-Ritz method, Galerkin method, reciprocal theorem

Suggested readings:
Advanced Mechanics of Materials, Boresi and Sidebottom, 4th edition, Wiley, 1985
Dynamics of Structures, Clough and Penzien, 2nd edition, McGraw-Hill, 1993
Failure of Materials in Mechanical Design, Collins, 2nd edition, Wiley 1993
Foundations of Solid Mechanics, Fung, Prentice-Hall, 1965
Energy and Finite Element Methods in Structural Mechanics, Shames and Dym, Hemisphere Pub., 1985
Theory of Elasticity, Timoshenko and Goodier, 3rd edition, McGraw-Hill, 1959
Stresses in Plates and Shells, Ugural, McGraw-Hill, 1981

MATERIALS

Topics:

Properties of engineering materials, selection factors for engineering applications

- Elastic, plastic, viscoelasticity, impact resistance, strain rate sensitivity
- Thermal properties – thermal schock resistance, effect of temperature on physical properties and deformation mechanisms
- Chemical properties – resistance to oxidation, corrosion, radiation

Failure modes in engineering applications – Yield, fracture, creep, fatigue, wear, corrosion

Ionic and molecular bonding, inter-molecular bonding

Effects on bulk properties of

- Atomic/molecular structure
- Point, line, and plane defects
- Grain microstructure
- Phase morphology and non-equilibrium compositions
- Discrete second phases – fibers, particles, inclusions, pores

Micro-mechanisms for mechanical failure

- Plastic deformation, void coalescence, crack propagation, creep, fatigue

Control of bulk properties – strengthening mechanisms

- Single phase materials vs. multi-phase materials
- Thermal processing – heat treatment, annealing, recrystallization, solution treatment
- Mechanical processing – cold working, machining, anisotropy
- Chemical processing – carburizing, nitriding, ion implantation

Basic properties and specifications of materials:

- Iron & steels, aluminum alloys, copper alloys
- Ceramics and glasses
- Polymers – thermoplastics, thermosets, elastomers
- Widely used composites

Suggested Readings:

Materials Science and Engineering An Introduction, Callister, 2^{nd} edition, Wiley, New York, 1985
Selection and Use of Engineering Materials, Charles and Crane, 2^{nd} edition., Prentice Hall, 1989
Engineering Materials, Properties and Selection, Budinski, 3^{rd} edition., Prentice Hall, 1989

Topics for Ph.D. Qualifier Exam
Control Systems

Text: *Modern Control Systems,* Dorf & Bishop, 7^{th} Ed., Addison-Wesley

Topics:

Mathematical Modeling of Physical Systems
- Linear differential equations of motion
- Laplace transforms and partial fractions
- Block diagram representations
- Transfer functions
- Linearization of nonlinear models

Feedback Control System Characteristics and Performance
- Open vs. closed loop control
- Transient and steady-state response
- Parametric sensitivity, disturbances, and noise
- Time & Laplace domains
- Steady-state error

Stability of Feedback Control Systems
- Characteristic equation and its roots
- Roth-Hurwitz criterion

Root Locus Method
- Sketching; target regions; frequency and damping ratios for specified pole locations

Frequency Response Methods
- Bode diagrams (sketching; break frequency; gain and phase margins)
- Adding poles and zeros

Compensation
- PID (Proportional/Integral/Derivative) control
- Phase-lead and phase-lag control
- Pole placement

State-Space (State Variable) Representation
- Transfer function matrix (Cramer's rule to extract individual transfer functions)
- Eigenvalues/Eigenvectors
- Modes(frequencies, damping ratios, and time constants)

Topics for Ph.D. Qualifier Exam
Dynamics & Vibrations

Texts:

Engineering Mechanics – Dynamics (Meriam & Craig), Wiley
Theory of Vibration with Applications (Thompson), Prentice-Hall.

Topics:

Two and Three Dimensional Kinematics of Rigid Bodies
- Angular Velocity and Angular Acceleration
- Derivative of a Vector in Multiple Reference Frames
- Relative Motion of Two Points Fixed on a Rigid Body
- Motion of a Point that is Moving on a Rigid Body – Coriolis acceleration

Inertia, Momentum, and Kinetic Energy
- Inertia Matrix (Moments and Products of Inertia)
- Principal Axes
- Parallel Axis Theorem
- Angular Momentum
- Kinetic Energy

Newtonian Dynamics
- Newton's Laws of Motion
  - Forces/Torques Required to Produce Desired Motion
  - Differential Equations of Motion
- Euler's Equations of Rotational Motion

Lagrangian Dynamics and Virtual Work
- Virtual Displacements
- Generalized Forces
- Principle of Virtual Work
- Lagrange's Equations of Motion

Vibration of Single- and Multi-Degree of Freedom Systems
- Free, Forced, and Transient
- Damped and Undamped

Vibration of Simple Continuous Systems
- Strings, Rods (longitudinal and torsional), and Beams