QUALIFYING EXAMINATION GUIDELINES FOR PH.D. STUDENTS

IN THE

DEPARTMENT OF AEROSPACE & MECHANICAL ENGINEERING

May 2026

Aerospace and Mechanical Engineering Department
College of Engineering
University of Arizona
Tucson, Arizona 85721
http://www.ame.arizona.edu
(520) 621-4692

GENERAL REMARKS

This booklet was prepared for the benefit of the student and should be read in conjunction with the Graduate Catalog and the Handbook of Graduate Programs in the Department of Aerospace and Mechanical Engineering. The purpose of this booklet is to help the student to prepare for the Ph.D. Qualifying Examination.

In order to continue their doctoral studies, all Ph.D. students are required to pass the Qualifying Examination. The intent of the qualifying examination is to evaluate the student's knowledge and understanding of the materials covered in the examination and to evaluate the student's potential to successfully complete a Ph.D. research program. Thus, while knowledge of the material and mathematical techniques covered in the individual examinations is important, the faculty look for much more than the ability to just memorize material. It is important that the candidate also have a good overall integrated understanding of the fundamentals of the material so that he/she can:

- properly relate the mathematical techniques and physical principles and apply these to engineering problems;
- apply the material to a wide range of situations including situations the student may not have previously seen; and
- be able to demonstrate the ability to think about problems in a logical and appropriate manner.

Please note that Ph.D. students are not eligible to register for dissertation units (AME 920) until the Qualifying Examination has been passed.

DEADLINES FOR COMPLETING THE QUALIFYING EXAMINATION

The deadline for taking the Qualifying Examination differs, depending on the student’s previous degree, and, in the case of students who already have an M.S. degree, the institution of study for their previous degree:

- Students who completed the requirements for the **M.S. degree with the University of Arizona** AME Department must take the Qualifying Examination no later than their second semester in residence for the Ph.D. degree (second semester of their first year).

- Students who completed the requirements for the **M.S. degree at another institution** must take the Qualifying Examination no later than their third semester in residence for the Ph.D. degree (first semester of their second year).

- Students who are on the **direct B.S. to Ph.D.** track must take the Qualifying Examination no later than their fifth semester in residence for the Ph.D. degree (first semester of their third year).

EXAM STRUCTURE

Qualifying Examinations are given twice a year, starting Monday of the second week of classes in the Fall and Spring semesters. (Exceptions to this schedule may occur when the second week of classes for the semester falls on a scheduled holiday break or because of an event such as a conference).

The written portions for the two subject areas will be administered as follows: **Engineering Mathematics on Monday and a second subject on Tuesday.** If a student obtains a numerical score below 60 on the written examination, an oral exam must be scheduled for that subject area. **The oral portions of the exam, if needed, will be scheduled for Thursday and Friday.** For each area, the test consists of a closed-book, written portion of two hours' duration; the oral portion (if needed) is of one hour's duration. The written portion of the exam is administered to students in a group setting, whereas the oral exams are scheduled and administered individually.

Each student must choose Engineering Mathematics and one other examination area/second subject. Material on the tests is at the Master level. The Associate Department Head to the Graduate Program selects two examiners in each area who will be responsible for preparing and grading each exam.

The subject areas for the Qualifying Examination are:

Engineering Mathematics
Fluid Mechanics
Dynamics and Controls
Solid Mechanics
Thermal Sciences

PASS POLICY

An AME Faculty Meeting is generally called the following week to determine a Pass/Fail decision for each student. Each student is notified by mail as soon as possible after the results of the examinations are decided.

Effective Spring 2018, students who fail either the Math or second subject Qualifying Exam may be granted a second Qualifying Examination to pass the subject(s) in which the student received a failing score(s). The second attempt to pass the Qualifying Exam must be completed in the following semester.

In the case that a student fails both the Math and subject exam in the first attempt, the student must attempt to pass both exams in the following semester.

No more than two attempts to pass each subject examination are permitted within AME, even if the student transfers between the Aerospace Engineering and Mechanical Engineering programs.

PREPARING FOR THE QUALIFYING EXAM

Suggested preparatory courses for the Qualifying Exams are:

Subject Area	Preparatory Courses
Engineering Mathematics	AME 500A, AME 500B
Fluid Mechanics	AMAE 536A, AME 536B
Dynamics and Controls	AME 550, AME 558
Solid Mechanics	AME 561, AME 564A
Thermal Sciences	AME 530, AME 532

Additionally, copies of past Qualifying Exams will be sent to students for reference and are available upon request.

Finally, listed on the following pages are the names of potential examiners for each subject area, as well as typical textbooks illustrating the topics covered and the level of the material are listed for each subject area.

ENGINEERING MATHEMATICS

Professors Wu, Hacker, Madenci, Zhupanska

Preparatory Courses
AME 500A, AME 500B

Students are expected to have mastered the basic concepts of differentiation and integration, infinite series and sequences, Fourier series, Laplace transforms, algebra of vectors and complex numbers, and ordinary differential equations in their undergraduate courses. Advanced concepts as well as the undergraduate concepts covered more in depth are generally considered in AME 500A and AME 500B, Advanced Engineering Mathematics.

Topics - AME 500A

Physical Vectors and Second Order Tensors

Ref. 1, CH 9, 14 – 16. Or Ref. 2, CH 9, 10
Ref. 3, CH 1-6, 8
Ref. 6, CH 8, 9

Cartesian coordinates; Representation of vectors and second order tensors (basis, components, etc.)
Index notation and summation convention
Algebra of vectors (addition, multiplication by scalar, dot and vector products, magnitude, direction, orthogonality)
Geometric interpretation of vector algebra
Vector fields; Tensors and tensor fields
Coordinate transformation of vector and tensor components
Grad, div, curl; identities

Curves (tangent, normal, curvature, torsion, etc.) and surfaces (tangents, normal, curvatures, etc.); Parametric representations; Arclength; Element of surface
Line, surface and volume integrals; Integral theorems (Gauss, Stokes, etc.)
General orthogonal coordinate systems; Coordinate metrics; Element of volume; Unit vectors; Differential operators

Topics AME 500A (continued)

Linear Algebra

Ref.4, CH 1-6
Ref. 6, CH 17 -20

Scalars and vectors; Vector spaces
Algebra of vectors (addition, multiplication by scalar); Geometry in $\square^3$
Linear combinations; Linear independence/dependence; Basis; Dimension
Subspaces; Spans; Reduction of spanning set to basis
Linear functions on vector spaces; Matrices; Algebra of matrices (addition, multiplication by scalar, matrix multiplication, inverse, etc.)
Change of basis; Matrix similarity
Linear equations; Row operations; LU factorization
Null space and range (nullity, rank, etc.); Solvability
Eigenproblem; Generalized eigenproblem; Diagonalization; Jordan form
Inner product; Orthogonality; Complements
Adjoint operator; biorthogonality; Green's function
Eigenproblem for self-adjoint operators
Real quadratic forms; Rayleigh-Ritz

Ordinary Differential Equations

Ref. 1, CH 1–4 <u>Or</u> Ref. 2, CH 1-5
Ref.4, CH, 5
Ref. 6, CH 20 - 23

Classification of ODE; Linear systems; Linearization about a solution
Solution of $d\mathbf{y}/dt = A\mathbf{y} + \mathbf{b}(t),\ A = const$ by matrix methods; Fundamental matrix
Power series solution about regular point
Series solution about singular point (Frobenius method); solution at infinity

Topics - AME 500B

Functions of a Complex Variable

Ref. 1, CH 21 - 24 <u>Or</u> Ref. 2, CH 13-18
Ref. 6, CH 11-15

Representation of complex numbers (ordered pair, $i-$notation, polar form, etc.)
Algebra of complex numbers (addition, product, roots, etc.)
The complex plane; geometric interpretation of algebra
Examples of functions of a complex variable; Isolated singularities (poles)
Multi-valuedness; Branch points and cuts
Differentiation; Cauchy-Riemann equations
Contour integration; Cauchy integral theorem; Deformation of contour; Cauchy integral formula
Taylor and Laurent expansions
Cauchy residue theorem
Analytic continuation; Evaluation of real integrals by residues

Examples of inversion of transforms; Contour deformation; Asymptotic considerations

Partial Differential Equations

Ref. 5, CH 1-13

Ref. 6, CH 26 - 28

First order linear, quasi-linear and nonlinear equations; method of characteristics; initial value problem
Second order equations in two variables; classification; normal forms; method of characteristics
Sturm-Liouville problem for second order equations (two-point eigenproblem); eigenfunction expansion.
Generalized functions (step, delta, etc); Green's function for second order ODE's,
Solutions of wave equation, diffusion equation and Laplace equation (finite domains, rectangular, cylindrical and spherical) using various techniques/boundary conditions
Solutions of wave equation, diffusion equation and Laplace equation (infinite domains) using various techniques/boundary conditions. Eigenproblem; Green's function for PDE's. Solutions by Fourier and Laplace transforms.

References:

1. M. Greenberg, Advanced Engineering Mathematics, 2nd edition, Prentice-Hall, 1998
2. E. Kreyszig, Advanced Engineering Mathematics, 9th edition, Willey & Sons, 2006
3. D. A. Danielson, Vectors and Tensors in Engineering and Physics, 2nd edition, Westview Press, 2003
4. G. Strang, Linear Algebra and its Applications, 4th edition, Brooks/Cole, 2006
5. R. Haberman, Applied Partial Differential Equations, 4th edition, Pearson Education, 2004
6. M. D. Greenberg, Foundations of Applied Mathematics, Dover, 2014

FLUID MECHANICS

Professors Craig, Fasel, Jacobs, Parent, Shkarayev, Wygnanski, Zohar, Threadgill, Hader

Preparatory Courses
AMAE 536A, AME 536B

The candidate must (1) demonstrate an understanding of the fundamentals of fluid mechanics at the level of AME 536A and 536B and (2) be able to apply these fundamentals to the solution of problems. Topics that the candidate will be expected to know include:

Control Volume Analysis: All conservation laws (Ref. 2)

Euler's Equations in Streamline Coordinates, **Bernoulli's Equation** (Ref. 2)

Dimensional Analysis and Similitude (Ref. 3, pp. 175-209)

Kinematics: Stress and rate of strain tensors (Ref. 1, pp. 131-147, Ref. 3, pp. 63-84)

Navier-Stokes Equations: Derivation and assumptions involved (Ref. 1, pp. 147-173, Ref. 3, pp. 87-146).

Potential Flow Theory (Ref. 1, pp. 378-471, Ref. 3, pp. 471-579)

Parallel and Nearly Parallel Viscous Flows: Lubrication theory (Ref. 1, pp. 216-228, Ref. 3, pp. 148-172

Low Reynolds Number Flow: Stokes and Oseen approximations (Ref. 1, pp. 216-246, Ref. 3, pp. 660-704).

Vorticity Dynamics (Ref. 1, pp. 264-282, Ref. 3, pp. 324-357)

High Reynolds Number Flows: Boundary layers, jets, and wakes (Ref. 1, pp. 303-353, Ref. 3., pp. 581-657)

Drag and Flow Separation (Ref. 3, pp. 359-400)

References:

1. G. K. Batchelor, Introduction to Fluid Mechanics, Cambridge University Press, 1980.
2. R. W. Fox and A. T. McDonald, Introduction to Fluid Mechanics, 3rd Ed., Wiley, 1985.
3. R.L. Panton, Incompressible Flow, 2nd Ed., Wiley, 1996.
4. M. Van Dyke, An Album of Fluid Motion, Parabolic, 1982.
5. C. Pozrikidis, Introduction to Theoretical and Computational Fluid Dynamics, Oxford, 1997.
6. Hermann Schlichting, Boundary Layer Theory, 7th Edition, New York: McGraw-Hill, 1979.

Dynamics and Controls

Professors Enikov, Shkarayev, Butcher, Larsson, Rastgoftar, Thanga

Preparatory Courses
AME 550, AME 558

The details of the dynamics (A) and controls (B) parts are explained below.

A) Dynamics

The dynamics part of the exam will be based on content from AME 550 **.** This course is designed to teach graduate students specializing in mechanics the basic principles of writing equations of motion for systems of particles and rigid bodies and solving the equations analytically and numerically. A review of Newton's laws of motion is followed by impulse-momentum methods, the derivation and use of Euler's equations and Lagrange's equations. The motion and behavior of spinning satellites, airplanes, tops, and gyroscopes are examined as examples of complex three-dimensional rigid body behavior. Non-linear dynamics will be presented including limit cycle oscillations and chaos.

The following topics have been highlighted to give the student a framework to prepare for the Qualifying Examination:

Basic Concepts: Newton's laws of motion, units, dimensions kinematics of particles and rigid bodies

Dynamics of Particles: Work, kinetic energy, potential energy, conservative systems, linear impulse and momentum, angular impulse and momentum, friction, equations of motion, collision, conservation laws.

Dynamics of Rigid Bodies: Virtual displacement and virtual work; generalized forces; impulse and momentum; impact; Newton's equations, Euler's equations, Lagrange's equations, D'Alembert's principle; dynamics of constrained and unconstrained systems; holonomic and nonholonomic constraints; Lagrange multipliers.

Vibration Theory: Free vibration of a conservative system; forced vibration of a conservative system; damped vibration; natural frequencies and mode shapes of single- and multi-degree of freedom systems, linearization of equations of motion.

Non-linear Dynamics: Two-dimensional non-linear dynamic systems, Phase portraits, Van der Pol equation, limit cycle oscillations, strange attractors, chaos.

References:

1. J. H. Ginsberg, Advanced Engineering Dynamics, 2nd Ed., Cambridge University Press, 1995.
2. W. T. Thomson, Theory of Vibrations with Applications, 3rd Ed., Prentice Hall, 1988.
3. P.E. Nikravesh, Computer-Aided Analysis of Mechanical Systems, Prentice-Hall, 1988.
4. S. H. Strogatz, Nonlinear Dynamics and Chaos, Westview Press, 2000.

B) Controls

Material from classical control is assumed knowledge that is generally taught at the undergraduate level (e.g., AME 455). See references [1] and [2] for a review of topics relating to classical control theory. Topics relating to modern control are covered in AME 558.

Classical Control: Differential equations and mathematical modelling of dynamical systems; Laplace Transforms; Solution of differential equation in time and Laplace domains; Transfer functions & block diagrams; Poles and zeros; Impact on poles and zeros on system response; First and second order systems; First- and second-order system approximation; Time-domain specifications (time constant, percent overshoot, settling time, etc.); Routh stability criterion; PID control.

Modern Control: Topics relating to modern control are covered in AME 558.

Basic Concepts: Linear algebra; Eigenvalues and eigenvectors; Fundamental subspace; Basis, dimension, and span; Determinants; Similarity transformations and common matrix decompositions (SVD, QR, LQ, Jordan, and Schur); Nonnegative definite and positive definite matrices.

State-space description of dynamical systems: Development of state-space model from differential equations; Determining system response in time and frequency domains; System impulse response and convolution; Linearization of non-linear systems; Determining state-space representations from transfer functions (and vice-versa); State transformations; Matrix exponential.

Stability of linear state-space systems: Eigenvalue analysis; Jordan form; Geometric and algebraic multiplicity of eigenvalues and influence on stability; Lyapunov stability theory for linear systems (the Lyapunov equation and solution; Lyapunov stable, asymptotically stable, and exponentially stable systems; Global and local stability).

Controllability and Observability: Concepts of controllability and observability; Controllable and unobservable subspaces; Implications of controllability/stabilizability and observability/detectability on controller and observer design; Uncontrollable and unobservable system decompositions; Determining controllability/observability/stabilizability/detectability of linear systems; Controllable and Observable canonical forms; Duality.

Control and Observer Design: Full-state feedback; Eigenvalue design and placement for control and state-observation; Luenberger observer; Observer-based compensation; Separability; Bass-Gura and Ackermann's methods; Steady-state tracking.

Optimal Regulation: The infinite-horizon Linear Quadratic Regulator (LQR) problem; Formulation, solution and the algebraic Riccati equation (ARE).[1]

References:

1. K. Ogata, Modern control engineering, 5th Ed., Pearson, 2009.
2. G. Franklin, J. Powell, and A. Emami-Naeini, Feedback control of dynamical systems, 6th Ed., Pearson, 2009.
3. T. Kailath, Linear Systems, Prentice-Hall, 1980.
4. R. Williams, D. Lawrence, Linear state-space control systems, John Wiley & Sons, 2007.
5. J. Hespanha, Linear systems theory, 2nd Ed., Princeton University Press, 2018.
6. W. Brogan, Modern Control Theory, 3rd Ed., Prentice-Hall, 1991.
7. G. Strang, Linear algebra and its applications, 4th Ed., Cengage Learning, 2006.

[1] Students will only be asked fundamental questions regarding the infinite-horizon LQR problem that examine their general understanding of the problem formulation and solution structure/procedure. Students are not required to know how to derive the LQR solution using variational calculus.

SOLID MECHANICS

Professors Missoum, Madenci, Wu, Zhupanska

Preparatory Courses
AME 561, AME 564A

The subjects listed here were selected for their fundamental nature. The examination will address the advanced student, whose mastery of the fundamentals allows their application to non-trivial situations. The lists of courses and textbooks are given to suggest the level of knowledge that is expected. The list is intended only as a guide.

COURSES

The following is a list of courses offered at The University of Arizona that are relevant to the Solid Mechanics major area:

Finite Element Analysis	AME 561 or equivalent
Advanced Finite Element Analysis	AME 563 or equivalent
Mechanics of Deformable Solids (I)	AME 564A or equivalent
Mechanics of Deformable Solids (II)	AME 564B or equivalent
Composite Materials	AME 562 or equivalent

*If the above courses are not taught due to cancellation, an equivalent may be taken

References:

1. Y. C. Fung, Fundamentals of Solid Mechanics, Prentice Hall, 1965.
2. S. P. Timoshenko and J. N. Goodier, Theory of Elasticity, McGraw Hill, 1970.
3. A. Mendelson, Plasticity: Theory and Applications, Macmillan, 1968.
4. R. D. Cook, D. S. Malkus, and M. E. Plesha, Concepts and Applications of Finite Element Analysis, John Wiley and Sons, 1989.
5. Y.C. Fung, A First Course in Continuum Mechanics, Prentice-Hall, latest edition.

THERMAL SCIENCE

Professors Hao, Li, Zohar, Beidaghi

Preparatory Courses
AME 530, AME 532

In addition to familiarity with the following subjects, the candidate is expected to be able to integrate theoretical tools and basic physical principles in simple applications. Familiarity with the course content of AME 530 (Advanced Thermodynamics and Radiation) and 532 (Conduction and Convection) is required. References are given as suggestions to indicate the level of the material covered.

Thermodynamics: Energy balances in closed and open systems; second law applications and derivations of limiting trends in systems; state principles and equations of state; applications to cycles (Ref. 1).

Convection: Physical driving mechanisms; laminar and turbulent regimes; forced and free convection; internal and external flows; uni-directional solutions; boundary layer approximations; scaling; asymptotic limits of high and low Prandtl numbers (Ref. 2).

Conduction: Fundamentals of heat conduction; Steady, 1-D conduction; Steady, multi-dimensional conduction; Transient conduction with steady boundary conditions; Transient conduction with time dependent boundary conditions. (Ref. 3).

Radiation: Definitions of radiative properties and fluxes, characteristics of blackbody radiation, basic laws (Planck's Law, Wien's Law, the Stefan-Boltzmann Law, Kirchhoff's Law), view factors, radiative exchange between diffuse, gray surfaces in an enclosure. (Ref. 4, Ch 1, 2, 5-7).

References:

1. A. Bejan, Advanced Engineering Thermodynamics, 3rd Edition, Wiley, 2006.
2. W. M. Kays and M. E. Crawford, Convective Heat and Mass Transfer, 4th Edition, McGraw-Hill, 2005.
3. M.N. Oziski, Heat Conduction, 2nd Edition, Wiley Interscience, 1993.
4. R. Siegel and J. Howell, Thermal Radiation Heat Transfer, 4th Edition, Taylor & Francis, 2002. (Chapters 1,2,5,6 and 7)