

AE PhD Qualifying Examination Courses and Topics

- Eleven (11) exam areas are offered twice per year (normally 2nd week of classes in Fall and Spring semesters)
- Qualifying Exams are designed for Ph.D. students to demonstrate mastery in 2 of the 6 discipline areas in AE:
 - Students select one exam in two different discipline areas.

Discipline Areas	Qualifying Exam Options	Primary Graduate Courses (Also see notes below table)
<i>Aerodynamics and Fluid Mechanics (AFM)</i>	Fluid Mechanics	AE6009 (Viscous Flow) and AE6012 (Turbulent Flow)
	Aerodynamics	AE6009 (Viscous Flow) and AE6015 (Advanced Aerodynamics)
<i>Aeroelasticity and Structural Dynamics (ASD)</i>	Dynamics and Structural Dynamics	AE6210 (Advanced Dynamics I) and AE6230 (Structural Dynamics)
<i>Flight Mechanics and Controls (FMC)</i>	Flight Dynamics	AE6530 (Multivariable Linear Systems and Controls) and AE6520 (Advanced Flight Dynamics)
	Controls	AE6530 (Multivariable Linear Systems and Controls) and AE6580 (Advanced Nonlinear Control)
<i>Propulsion and Combustion (PC)</i>	Gas Dynamics	AE6765 (Kinetics and Thermodynamics of Gases) and AE6050 (Gas Dynamics)
	Combustion	AE6765 (Kinetics and Thermodynamics of Gases) and AE6766 (Combustion)
<i>Structural Mechanics and Materials (SMM)</i>	Structural Mechanics and Materials	AE6114 (Fundamentals of Solid Mechanics) and AE6115 (Fundamentals of Aerospace Structural Analysis)
<i>Systems Design and Optimization (SDO)</i>	Fixed Wing Vehicles	AE6310 (Optimization for Design of Engineered Systems) and AE6343 (Aircraft Design I)
	Space Vehicles	AE6310 (Optimization for Design of Engineered Systems) and AE6353 (Orbital Mechanics)
	Rotary Wing Vehicles	AE6310 (Optimization for Design of Engineered Systems) and AE6333 (Rotorcraft Design I)

- The general scope of each area's exam is inclusive of topics covered in primary courses as well as prerequisites, and background material at the graduate and undergraduate level.
 - **Prerequisite and background material not covered in the primary graduate courses is also included in the examinations. Some of that material may come from topics typically covered in undergraduate coursework.**
 - **A list of topics for each of the examination areas is provided below...**

Aerodynamics and Fluid Mechanics (AFM) Ph.D. Qualifying Exams

Two exam tracks are offered by AFM:

- **Fluid Mechanics**

- Includes the Viscous Flow topics and Turbulence topics shown on the following pages
 - This exam track focuses primarily on laminar, transitional and turbulent effects within fluid mechanics
- The topics included typically span both graduate and undergraduate coursework
- At Georgia Tech the topics are typically included in the following courses:
 - AE6009 Viscous Flow
 - AE6012 Turbulent Flow
 - AE3030 Aerodynamics

- **Aerodynamics**

- Includes the Viscous Flow topics and Aerodynamics topics shown on the following pages
 - This exam track focuses on inviscid and viscous aerodynamics from incompressible through hypersonic flight
- The topics included typically span both graduate and undergraduate coursework
- At Georgia Tech the topics are typically included in the following courses:
 - AE6009 Viscous Flow
 - AE6015 Advanced Aerodynamics
 - AE3030 Aerodynamics

Viscous Flow

- Viscous Flow Basics
 - Navier Stokes equations and derivation
 - Viscous Stresses
 - Non-dimensionalization and Dynamic Similarity
 - Vorticity transport
- Exact Solutions of the Navier-Stokes Equations
 - Parallel Flows
 - Unsteady Flows
- Incompressible Laminar Boundary Layer
 - Boundary Layer Approximations
 - Similarity Solutions – General and Particular Solutions
 - Flow physics and prediction of incompressible boundary layer properties
- Compressible Boundary Layers
 - Effect of compressibility on boundary layer properties
 - Similarity Solutions
 - Thermal Boundary Layers
 - Flow physics and prediction of compressible boundary layer properties
- Transition to Turbulence
 - Linear-Stability Analysis
 - Orr-Sommerfield equation and temporal stability analysis
 - Prediction of transition, relevance to turbulence and transition flow physics
 - Non-Linear Stability analysis
- Boundary Layer Separation
 - Pressure gradient effects and flow physics associated with separation
 - Singularities in 2D and 3D boundary layers
 - Criteria and analytical representation
- Free Shear Layers
 - General Similarity Solutions
 - Jets, Wakes and Mixing Layers

Turbulence

- Turbulence Basics
 - Basic concepts, length scales and time scales
 - Navier-Stokes equations in tensor form
 - Reynolds averaging and the closure problem
 - Turbulence research: experiments, theory, modeling
 - Turbulence research: the role of advanced computation
- Energy and scale relations
 - Kinetic energy equation and energy budget
 - Concepts of homogeneity and isotropy
 - Interscale energy transfer, small-scale universality
- Probability and statistics
 - Characteristics of one random variable
 - Characteristics of two random variables
 - Random processes
 - Statistical sampling
- Statistical and spectral description
 - Correlation and structure functions
 - Spectra in wavenumber space
 - Kolmogorov's similarity hypotheses
- Free shear flows
 - Momentum equations for almost parallel flows
 - Self-preserving wakes
- Wall-bounded shear flows
 - Mean velocity profile in a turbulent boundary layer
 - Inner and outer scalings, logarithmic region
- Turbulence Simulation and Modeling
 - Overview of various approaches
 - Turbulent (eddy) viscosity models
 - Second-order Reynolds stress modeling

Aerodynamics

- Governing equations and their simplifications across all speed regimes
 - Navier-Stokes Equations
 - Euler Equations
 - Full and Linearized Potential Equations
 - Transonic Potential Equations
- Concepts and assumptions of aerodynamics
 - Perfect gas, Kelvin's/Bernoulli equations, continuity of vorticity
 - Concepts of pressure, lift, drag and pitching moments and their coefficients
 - Visualization approaches for flow fields and surfaces
- Classical approaches from incompressible to supersonic
 - Estimates for airfoils, wings, and slender bodies
 - Incompressible and compressible Potential Flow
 - Thin Airfoil Theory and Finite Wing Theory
 - Effect of wing geometry (aspect ratio, sweep, twist, taper, etc.) on aerodynamic properties and coefficients
 - Lifting line (and extensions), vortex lattice
 - Effects of compressibility on aerodynamic properties around 2-D and 3-D bodies in subsonic and supersonic flow
 - Transonic flow effects
 - Supersonic linearized theory
- Integrated Aerodynamics
 - Effect of boundary layers and flow separation on aerodynamics of flat plates, airfoils and wings
 - Wing/Body/Fuselage Interactions
- Introduction to Unsteady Aerodynamics
 - Piston Theory
 - Vortex Flows
 - Separated Flows
 - Bluff Bodies
- High Angle of Attack Aerodynamics
 - Lift and Drag prediction
 - High lift devices
- Hypersonic Flows
 - Hypersonic aerodynamics prediction for blunt and sharp LE bodies:
 - Hypersonic Shock and Expansion Relations, Local Surface Inclination Methods

Aeroelasticity and Structural Dynamics (ASD) Qualifying Exam

A single qualifying exam is offered for this discipline group and it covers dynamics and structural dynamics. A listing of the topics is provided below

Dynamics

- Vector Mathematics
- Particle Kinematics
- Particle Dynamics
- Rigid Body Rotation
- General Motion of a Rigid Body
- Angular Velocity and Acceleration
- Two Points Fixed on a Rigid Body
- One Point Moving on a Rigid Body
- Kinematic Differential Equations
- Fundamentals of Newton/Euler Dynamics
- Mass Moment of Inertia
- Newton/Euler Dynamics
- Constraints
- Analytical Dynamics
- Multibody Dynamics
- Friction Modeling
- Impact and Contact Modeling
- Kinematics of material points or particles
- Kinematics of a rigid body in planar motion
- Kinetics of a rigid body in planar motion
- Special integrals of the equations of planar motion of rigid bodies (e.g., work and energy, impulse and momentum)
- Kinematics of rigid bodies in three-dimensions (including orientation angles, angular velocity)
- Kinetics of rigid bodies in three-dimensions (Euler's dynamical equations)
- Configuration constraints
- Motion constraints
- Generalized coordinates
- Inertia dyadics, matrices, and scalars.
- Lagrange's equations

Structural Dynamics

- Hamilton's principle

- Beams vibrating in extension, torsion, bending (development of complex boundary condition)
- Single-degree-of-freedom systems (equations, basic responses, response to harmonic excitation)
- Various kinds of damping
- Response of Single-degree-of-freedom systems to periodic excitation; Fourier series
- Laplace transforms
- Convolution and Duhamel's integrals
- Fourier integral; Fourier transforms
- Matrix eigenvalue problems (conservative and non-conservative systems)
- Rigid-body modes
- Vibration of membranes and plates
- Rayleigh's quotient
- Rayleigh-Ritz and Galerkin's methods
- Bending-shear vibration of Timoshenko beams
- Beams with axial force (including rotating beams and Beck's problem)

Flight Mechanics and Control (FMC) Ph.D. Qualifying Exams

Core Area: Linear Systems and Control (for both the Flight Dynamics and Controls exams)

Fundamentals of vibration and system dynamics

- Free and forced vibration, single- and multi-degree of freedom systems
- Modeling of aerospace and mechanical systems
- Energy methods, potential and kinetic energy for MDOF systems
- The eigenvalue-eigenvector problem, modal analysis
- Orthogonality of modes and system decoupling

Dynamic modeling in the state space

- Linear system analysis, ordinary differential equations, Laplace transforms
- Linear and nonlinear state space models, linearization, and realizations
- Free and forced response, resonance
- Harmonic steady state analysis
- Matrix second-order vibrational systems
- Stability of linear systems: Lyapunov stability, semistability, and asymptotic stability

Linear system analysis in the frequency domain

- Frequency response
- Bode gain and phase diagrams

Control system analysis and design

- Transfer functions, block diagrams, and signal flow graphs
- Stability analysis, transient performance, steady state error
- Routh's stability criterion
- Root locus techniques
- PI, PD, and PID controllers
- Effect of poles and zeros on system response, pole-zero cancellations

Frequency domain analysis and design of control systems

- Bode gain and phase diagrams
- Gain and phase margins, relative stability margins, robustness
- Lead and lag dynamic compensation
- Nyquist diagrams and Nyquist stability criterion

Matrix Mathematics

- Matrix Decompositions (Jordan, Schur, Singular Value)
- Nonnegative Definite and Positive Definite Matrices
- Matrix norms, Generalized Inverses
- The Matrix Exponential

Linear System Theory

- Controllability, Observability, Stabilizability, Detectability
- Lyapunov Functions, Lyapunov Equations
- H₂ Norm: Deterministic Formulation
- H₂ Norm: Stochastic Formulation

Filter and Controller Synthesis

- The Standard Problem
- The Linear-Quadratic Regulator Problem (LQR)
- Analysis of the Algebraic Riccati Equation
- Static Output Feedback Controllers
- Least Squares Estimation Theory
- The Kalman Filter and The Observer Riccati Equation
- The Linear-Quadratic-Gaussian Problem (LQG)
- Full-Order Dynamic Compensation and the Separation Principle
- Model Following

Frequency Domain Concepts

- Frequency Domain Properties of the LQR and LQG Problems
- Guarantees of Phase and Gain Margins
- The Return Difference Equality
- Internal Stability
- The Multivariable Nyquist Criterion
- Sensitivity/Complementary Sensitivity
- MIMO Performance Specifications

Part 1. Flight Dynamics

- Aircraft equations of motion, Euler angles
- Aircraft longitudinal and lateral modes (short period, phugoid, etc)
- Aircraft stability derivatives, aircraft static stability
- Aircraft flying qualities
- Attitude Kinematics, Quaternions
- Aircraft Control Design (Yaw dampers, SAS, etc)
- Inertial Navigation, GPS

The aforementioned topics should be viewed as a minimum competency requirement for the flight dynamics and control breadth area exam and are covered in AE 3515 and AE 3521 (or AE6520).

Part II. Controls

Nonlinear Dynamical Systems and Differential Equations

- System Equilibria

- Nonlinear Differential Equations
- Dynamical Systems, Flows, and Vector Fields
- Existence and Uniqueness of Solutions
- Continuous Dependence on System Initial Conditions and Parameters
- Continuity, Uniform Continuity, and Lipschitz Continuity
- Limit Points, Limit Sets, and Attractors

Nonlinear Second-Order Dynamical Systems

- Vector Fields, Flows, Phase Portraits
- Nodes, Saddles, Foci, and Centers
- Isocline Method and Linearization
- Periodic Orbits and Limit Cycles
- Poincare, Bendixon, and Poincare-Bendixon Theorems

Stability Theory for Nonlinear Dynamical Systems

- Lyapunov Stability, Asymptotic Stability, Exponential Stability
- Lyapunov Stability Theorems
- Lyapunov Function Constructions
- Krasovskii's Method, Variable Gradient Method, Zubov's Method
- Stability of Linear Systems and Lyapunov's Linearization Method
- Invariance Principal
- Invariant Set Stability Theorems

Passivity and Nonexpansivity Theory for Nonlinear Dynamical Systems

- Storage Functions, Supply Rates, Available Storage, Required Supply
- Positive Real and Bounded Real Dynamical Systems

Absolute Stability Theory

- The Lure Problem
- Positivity Theorem, Circle Theorem, Popov Theorem
- Stability of Feedback Interconnections
- Small Gain and Positivity Theorems

The aforementioned topics should be viewed as a minimum competency requirement for the flight dynamics and control core area exam and are covered in AE 6531, AE 6580, and AE 6520.

Propulsion and Combustion (P&C) Qualifying Exam Topics

Thermodynamics (for both the Gas Dynamics and Combustion exams)

Classical Thermodynamics

- Conservation Equations
 - Energy and the 1st Law
 - Entropy and the 2nd Law
 - Control mass and control volume approaches
- Thermodynamic properties
 - General conditions for equilibrium (including phase, chemical equilibria)
 - State equations and Maxwell's relations and application to gases
- Chemical (and phase) thermodynamics for perfect and imperfect gases
 - Equilibrium constant
 - Standard reference states

Statistical Thermodynamics

- Quantum mechanics models for energy states
- Distribution over energy states, Boltzmann limit/Boltzmann's distribution
- Boltzmann's Relation
- Ideal gas properties from statistical mechanics
 - Partition functions
 - Translation, rotational, vibrational, and electronic modes
- Equilibrium constant

Gas Kinetic Theory

- Maxwell distribution
- Molecular fluxes
- Collision rates, collision frequency and mean free path

Gas Dynamics

Compressible flows for thermally and calorically perfect gases

- Flow properties
 - Sound speed, Mach angle, Mach number, static and stagnation properties
- Effects of area change, heat transfer and irreversibility
- Isentropic nozzle flows and property relations
- Normal and oblique shocks and property relations
- Prandtl Meyer expansions and compressions and property relations
- Reflection of compression and expansion waves

Equilibrium and frozen gas flows

- Collisional vs flow times
- Equilibrium properties of high temperature air and ionization equilibrium
- Equilibrium and frozen speeds of sound
- Flows with area change (nozzles), shocks, and expansions

Nonequilibrium gas flows

- Energy relaxation rates: vibrational and chemical rates
- Inviscid nonequilibrium flows: shocks, expansions, nozzles, blunt bodies
- Translational nonequilibrium: Boltzmann equation, molecular transport properties
- Radiative energy transfer in gases

Combustion

Equilibrium properties of combustible mixtures

- Equivalence ratio, adiabatic flame temperature, major/minor combustion products

Chemical kinetics

- Gas phase reaction rates, reaction rate models and time scales
- Reaction mechanisms
 - Analysis and simple reduction assumptions (partial equil./steady-state)
 - Chain branching and explosions/autoignition
 - Fundamentals for simple hydrocarbon combustion mechanisms
- Reduced order modeling using flow reactors: autoignition, blowoff, emissions

Premixed laminar combustion

- Deflagrations and detonations: Rayleigh-Rankine-Hugoniot analysis
- Structure and propagation of 1-d detonations
- Laminar flames: structure, flame speed, flame thickness, stretch effects, quenching, ignition, flammability limits and static stability(flame holding)

Non-premixed laminar combustion

- Conserved scalars, diffusion-limited flames, finite-rate chemistry effects
- Applications including jet flames and droplet evaporation/burning

Turbulent Combustion

- Basic effects of turbulent mixing, transport and stretch on flames
- Combustion regimes and controlling physics in each

Structural Mechanics and Materials (SMM) Ph.D. Qualifying Exam Topics

○ Structural Analysis for PhD Qualification Exam

I. Fundamentals of Aerospace Structural Analysis

1. Euler Bernoulli beam
2. 3D beam theory
3. Torsion of beams
4. Thin-walled beams
5. Virtual work principles
6. Energy methods
7. Buckling
8. Shearing deformation in beams

II. Fundamentals of Solid Mechanics

1. Kinematics of deformation
2. Internal forces
3. Mechanical conservation and balance laws
4. Constitutive models
5. Boundary value problems in linear elasticity
6. Energy methods & introduction to FEM

Systems Design and Optimization (SDO) Ph.D. Qualifying Exams

Optimization for the Design of Engineered Systems Course Outline (for all SDO qualifying exam areas)

1. Introduction

- Need for numerical optimization in engineering design
- Review of multivariate calculus fundamentals

2. Unconstrained Optimization

- Necessary conditions for optimality
- Line search algorithms
 - Zeroth order (Powell's method, univariate search)
 - First order (steepest descent, Fletcher-Reeves conjugate gradient, BFGS, etc.)
 - Second order (Newton's method)
- Direct search algorithms (grid search, random walk, coordinate pattern search, etc.)
- Normalization approaches and convergence criteria

3. Constrained Optimization

- Challenges of constraints; activity, feasibility
- KKT necessary conditions for optimality
- Indirect methods and penalty functions (interior, exterior, augmented Lagrangian, etc.)
- Linear programming and the simplex method
- Direct methods (SLP, MoFD, generalized reduced gradient method, SQP, etc.)

4. Metaheuristic Optimization

- Metropolis algorithm and simulated annealing
- Binary representation (decimal/binary conversion, Hamming distance, Gray codes)
- Genetic operators and algorithms (selection, crossover, mutation, replacement)
- Particle swarm algorithms

5. Multi-Objective Optimization

- Partial ordering and Pareto dominance
- Aggregate objective function (AOF) approach

- ϵ -constraint method
- Normal boundary intersection (NBI) and related methods
- Multi-objective genetic algorithms (NSGA-II, etc.)

6. Multidisciplinary Optimization

- Multidisciplinary analysis (MDA): partitioning, interaction, coupling, consistency
- Design Structure Matrices (DSM)
- Fixed-point iteration (Gauss Seidel)
- Single-level MDO architectures (MDF, IDF)
- Multi-level/hierarchical MDO architectures (CO, ATC)

7. Designs of Experiments and Surrogate Models

- Full and fractional factorial designs
- Space filling designs (LHC, minimax and maximin, maximum entropy, uniform)
- Multiple linear regression models: polynomials and radial basis functions (RBFs)
- Nonlinear regression models: artificial neural networks (ANN) and Gaussian processes
- Assessing fit quality: error measures, validation sets, cross-validation, overfitting
- Regularization methods

8. Robust Design Methods

- Taguchi methods
- Probabilistic methods in robust design; approaches for uncertainty propagation
- Reliability-based design optimization (RBDO)

9. Bayesian Global Optimization

- Philosophical approach involving Bayesian surrogate models
- Expected improvement criterion
- Efficient Global Optimization (EGO)

I. Topics Outline for Orbital Mechanics

Basic Orbital Mechanics

- Newton's law of gravitation, N-body problem, Two-body problem
- Two-body orbital mechanics (Kepler's Laws, conic section orbits)
- Orbital elements
- Conservation of angular momentum and energy
- Earth orbits (LEO, GEO, etc.)

Orbit Determination

- Reference frames
- Determination of orbital elements from position and velocity
- Determination of position and velocity from orbital elements
- Spacecraft ground tracks and special orbits (LEO, GEO, SSO, Molyniya)

Orbital Maneuvers

- Orbit shaping and orbit transfer (ΔV 's, Hohmann transfers)
- Orbital plane change

Kepler's Problem: Time of Flight

- Time-of-flight for elliptic orbits (mean anomaly, eccentric anomaly)
- Time-of-flight for parabolic and hyperbolic orbits

Gauss' Problem: Intercept & Rendezvous

- p-iteration technique
- Universal variable formulation
- Mission design applications

Interplanetary & Lunar Trajectories

- Phase angle and synodic period
- The patched conic approximation (spheres of influence)
- Interplanetary trajectories, Gravity assist maneuvers
- Simple lunar transfers, Lunar free-return trajectories, The restricted 3-body problem

Space Vehicle Performance

- Basic vehicle performance (the ideal rocket equation)
- The modified rocket equation (with ascent losses included)
- Vehicle sizing and synthesis (structural and propellant mass fractions)
- Vehicle staging

Advanced Topics

- Orbital rendezvous
- Space navigation

The aforementioned topics should be viewed as a minimum competency requirement for the Orbital Mechanics area exam and are covered in AE 6353 (graduate course), as well as in AE 4310 (undergraduate course).

II. Topics Outline for Rotary Wing

Aerodynamics for rotary wing aircraft

- Momentum theory for hovering flight
- Blade element theory for hovering and forward flight
- Combined momentum and blade element theory for forward flight
- Power required for hover and forward flight performance
 - Induced power
 - Profile power
 - Parasite power
 - Impact of altitude and gross weight on helicopter performance, e.g. power Required

Propulsion for rotary wing aircraft

- Understanding of the basic processes of turboshaft and turboprop engines, including ideal and real Brayton cycle performance
- Understanding how power available is extracted from turboshaft engines and distributed to main and tail rotors; and possibility for auxiliary propulsion, e.g. propellers, fans, etc.

Rotary wing aircraft performance in hover and forward flight

- Hover capability, including both in ground effect (IGE) and out-of-ground effect (OGE)
- Forward flight capability, including cruise and endurance speed; best rate-of-time speed and max level flight speed
- Maneuver capability, including both steady and transient flight capability

Rotary wing aircraft design synthesis

- Fuel balance method, RF, for gross weight determination
- Power balance method for critical power loading determination
- Understanding of ten key rotary wing design parameters

III. Topics Outline for Fixed Wing

1. Requirements analysis and concept down-selection
 - a) Definition of requirement
 - b) Requirement Analysis
 - c) Mapping requirements to system design
2. Sizing and Synthesis
 - a) Constraint Analysis, Mission Analysis, Carpet Plots
 - b) Energy/Power based constraint analysis
 - c) Feasible/Infeasible design spaces, sensitivity of constraints
 - d) Alternative energy based sizing and synthesis
3. Aerodynamics
 - a) Atmospheric properties
 - b) Characteristics of different types of flows (subsonic, transonic, supersonic etc.)
 - c) Lifting line theory, Panel Methods, Elementary Flows, Vortices.
 - d) Overview of basic parameters (lift, drag), types of drag etc.
 - e) Aerodynamic coefficients and their variation (C_L , C_D , center of pressure etc.)
4. Performance
 - a) Equations of motions of aircraft
 - b) Performance characteristics (range, endurance, rate of climb, stall etc.)
 - c) Variations of thrust and power required
 - d) Steady and accelerated performance analysis (turns, load factor, gliding flight)
 - e) Take-off and landing performance
5. Propulsion
 - a) Types of propulsion systems and how they work
 - b) General engine trends (e.g., pressure, velocity, and temperature)
 - c) Brayton cycle analysis, efficiencies
 - d) Variation of engine performance (with velocity, altitude etc.)
6. Structures
 - a) Stress-strain relationships, constitutive behavior of materials
 - b) Composites and design considerations
 - c) V-n diagram, safety factors, fatigue performance, design approaches
 - d) Thin-walled structures
7. Stability and Controls
 - a) Definitions
 - b) Stability Modes
 - c) Stability and control on modern aircraft
8. Other Design Considerations
 - a) Subsystems
 - b) Airframe-Engine Integration

- c) Noise and Emissions
- d) Inlets, Exhausts, and Nacelles
- e) Commercial Engine Nacelles
- f) Survivability
- g) Alternative fuels

The aforementioned topics should be viewed as a minimum competency requirement for the Fixed Wing area exam and are covered in AE 6343 (graduate course), as well as following undergraduate courses: AE 4350, AE 3310, AE 3030.