

### AE PhD Qualifying Examination Courses and Topics

- Eleven (11) exam areas are offered twice per year (normally 2<sup>nd</sup> 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)
<b><i>Aerodynamics and Fluid Mechanics (AFM)</i></b>	Fluid Mechanics	AE6009 (Viscous Flow) and AE6012 (Turbulent Flow)
	Aerodynamics	AE6009 (Viscous Flow) and AE6015 (Advanced Aerodynamics)
<b><i>Aeroelasticity and Structural Dynamics (ASD)</i></b>	Dynamics and Structural Dynamics	AE6210 (Advanced Dynamics I) and AE6230 (Structural Dynamics)
<b><i>Flight Mechanics and Controls (FMC)</i></b>	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)
<b><i>Propulsion and Combustion (PC)</i></b>	Gas Dynamics	AE6765 (Kinetics and Thermodynamics of Gases) and AE6050 (Gas Dynamics)
	Combustion	AE6765 (Kinetics and Thermodynamics of Gases) and AE6766 (Combustion)
<b><i>Structural Mechanics and Materials (SMM)</i></b>	Structural Mechanics and Materials	AE6114 (Fundamentals of Solid Mechanics) and AE6115 (Fundamentals of Aerospace Structural Analysis)
<b><i>Systems Design and Optimization (SDO)</i></b>	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-Sommerfeld 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
- Kinematics of rigid bodies in two- and three- dimensions
  - Angular Velocity and Acceleration
  - Two Points Fixed on a Rigid Body
  - A Point Moving on a Rigid Body
  - 3D Finite Rotation
  - Kinematic Differential Equations
- Kinetics of rigid bodies in two- and three- dimensions
  - Mass Moment of Inertia Matrix
  - Newton/Euler Equations of Motion
  - Friction, Slipping, and Rolling
  - Conservation of Momentum and Energy
- Configuration and Motion constraints
- 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
- H<sub>2</sub> Norm: Deterministic Formulation
- H<sub>2</sub> 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 1<sup>st</sup> Law
  - Entropy and the 2<sup>nd</sup> 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. Foundational Mathematics

- Multivariate calculus
- Linear Algebra

## 2. Unconstrained Optimization: theory and gradient-based algorithms

- First-order necessary and second-order sufficient conditions for local optimality
- Convexity and global optimality
- Line search theory and methods (sufficient decrease, Wolfe, Armijo conditions, backtracking)
- Line search optimization algorithms (steepest descent, conjugate gradient, Newton's method, quasi-Newton methods)
- Trust region optimization theory and methods (Cauchy point, basic algorithm)

## 3. Constrained optimization: theory and gradient-based algorithms

- Standard canonical constrained optimization problem formulation
- KKT conditions, second-order necessary and sufficient conditions
- Penalty methods
- Augmented Lagrangian methods
- SQP
- Interior point methods

## 4. Multi-Objective Optimization

- Partial ordering and Pareto dominance

## 5. Simulation-based optimization

- Computational differentiation: direct method and adjoint method; automatic differentiation (AD), finite differences, complex step

## 6. Surrogate modeling

- Linear least squares regression
- Principal component analysis
- Nonlinear regression
- Regularization

## 7. Derivative-free optimization

- Genetic optimization
- Particle swarm optimization

## 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 ( $\Delta V$ '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.