Department of Aeronautics and Astronautics
School of Engineering
Massachusetts Institute of Technology

Graduate Program (S.M., Ph.D., Sc.D.)

Field: Aerospace Computational Engineering (ACE)
Date: September 4, 2007

1. Introduction and Purpose

The graduate program in the Department of Aeronautics and Astronautics at M.I.T. provides educational opportunities in a wide variety of aerospace-related topics through academic subjects and research. The purpose of this document is to provide incoming masters and doctoral level students guidance in planning the subjects they will take during their graduate program. The suggestions outlined here are to be understood as guidance and not as a mandatory, rigid framework. The final decision as to which subjects are taken and in what sequence is to be decided between each student and their academic advisor and/or doctoral committee. In addition to these recommendations, the official S.M. and doctoral degree completion requirements must be taken into account during the design of a graduate program[1].

2. Motivation for studying Aerospace Computational Engineering (ACE)

Intensive computation for simulation and optimization has become an essential activity in the design and operation of complex systems in engineering. While computational science is a discipline in itself, it serves to advance all of science and engineering. The fundamental role and challenges faced by computational science in today's society is well captured in two reports commissioned by the National Academy of Sciences[2] and the Executive Office of the President of the United States[3]

The National Academy report points out that revenues from simulation and optimization software products are already in the billions of dollars but the overall impact of these products is already in the trillions of dollars. Despite this already considerable development, the same report predicts that the next decade will experience an explosive growth in the demand for accurate and reliable numerical simulation and optimization of complex systems. The report makes an important distinction between computer science and computational science, the former referring to the science and technology pertinent to the computer, whereas the latter addresses the development of modeling and optimization technology and software for specific systems applications. The report also points out a

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[1] Refer to the S.M., Ph.D. and Sc.D. degree requirements in Aeronautics and Astronautics section of the MIT Bulletin, or to http://web.mit.edu/aeroastro/academics/grad/index.html
[2] Oden J.T. (ed.) Research Directions in Computational Mechanics, National Research Council Report, National Academy.
[3] Computational Science: Assuring America's Competitiveness, Report to the President, June 2005, President's Information Technology Advisory Committee.

critical weakness in the way most scientific policy-makers have acted until now: "There has been a tendency to promote investment in computer science as a necessary tool with which good computational science can be done, but there has been no comparable [investment] in the computational sciences necessary to do important applications."

A more recent report produced by the President's Information Technology Advisory Committee (PITAC) and entitled "Computational Science: Ensuring America's Competitiveness", warns of the dangers of underestimating the importance of computational science and not acting decisively. It continues to say that "Inadequate support [to computational science] has endangered US scientific leadership, economic competitiveness and national security". Below we give the principal finding and principal recommendation presented in that report:

PRINCIPAL FINDING

Computational science is now indispensable to the solution of complex problems in every sector, from traditional science and engineering domains to such key areas as national security, public health, and economic innovation. Advances in computing and connectivity make it possible to develop computational models and capture and analyze unprecedented amounts of experimental and observational data to address problems previously deemed intractable or beyond imagination. Yet, despite the great opportunities and needs, universities and the Federal government have not effectively recognized the strategic significance of computational science in either their organizational structures or their research and educational planning. These inadequacies compromise U.S. scientific leadership, economic competitiveness, and national security.

PRINCIPAL RECOMMENDATION

Universities and the Federal government's R&D agencies must make coordinated, fundamental, structural changes that affirm the integral role of computational science in addressing the 21st century 's most important problems, which are predominantly multidisciplinary, multi-agency, multisector, and collaborative. To initiate the required transformation, the Federal government, in partnership with academia and industry, must also create and execute a multi-decade roadmap directing coordinated advances in computational science and its applications in science and engineering disciplines.

3. What is Aerospace Computational Engineering?

Since the early days of computational mechanics the aerospace community has been at the forefront of computational science and engineering driven by a need for high accuracy models in the design of aerospace vehicles and systems. Not surprisingly, NASA has played a major role in the development of the early finite element codes for structural mechanics (e.g. NASTRAN) as well in the development of Computational Fluid Dynamics. Traditionally, the aerospace industry with companies such as, Boeing. Lockheed, Rolls Royce, Dassault, etc. has pioneered the use of the latest computational tools and in many cases they have developed highly sophisticated in-house capabilities through alliances with universities and research institutions. The origin of the more recent paradigms on multidisciplinary design and optimization (MDO) can also be traced back to the same community. The need for accurate and reliable prediction tools for complex engineering systems will continue within aerospace.

The department has had a strong presence in computational engineering, in particular but not exclusively in the areas of computational fluid dynamics and computational mechanics of materials. Currently, our department has several faculty and staff focused principally on research in computational engineering, e.g. Darmofal, Drela, Haimes, Peraire, Radovitzky, and Willcox, as well as several other faculty with a significant interest in computation.

4. **Aerospace Computational Engineering and Computational Design and Optimization (CDO) at MIT**

The critical role that computation now plays across all engineering disciplines, as well as the industry-based demand for engineers who are literate in computational sciences, has created a clear need to educate tomorrow's engineers in computational engineering. Recently, the School of Engineering has created a new interdepartmental S.M. program in Computation for Design and Optimization (CDO) to address this need (http://web.mit.edu/cdo-program/). Through the creation of this program, MIT recognizes the critical role that computational science plays in engineering. The current program has over 25 affiliate faculty members from the schools of engineering, science and Sloan with a strong representation from the Department of Aeronautics and Astronautics.

The CDO S.M. program will serve as a credential that establishes an educational standard in computational methodologies in engineering. As such, the CDO program is designed to support department efforts in computation. Since most of the faculty in the department with interests in ACE are also affiliated to the CDO program, there is a significant overlap and synergy between the two programs. At the SM level, we envisage that students will choose either program. The departmental SM with focus on ACE allows for a more focused emphasis on aerospace, whereas the interdepartmental CDO program is more generic. It is also possible for students interested in a dual SM to do both programs concurrently. The CDO SM program would also serve doctoral programs in the department whose students' research relies on computational methodologies. We envision some doctoral students in the Department will want to pursue CDO as a dual degree in order to gain necessary knowledge, as well as to certify their knowledge, of computational methodologies.

5. **Intellectual Content and Educational Objective**

Simply stated, at the SM level the ACE focus area aims to educate the professionals who will computationally model, optimize, control, and operate the important aerospace engineering systems of the next decade, as well as contribute to our own increasingly computationally intensive research programs within the Department. The program is designed with a common core that serves all disciplines, and an elective component to concentrate on particular applications.

The educational program is designed to emphasize: breadth through introductory courses in the areas of numerical linear algebra, discretization of partial differential equations and optimization methods; depth in the areas of materials and structures, fluid mechanics, propulsion and control; integration and multidisciplinary aspects; hands-on experience through a research based thesis.

6. SM Degree Requirements

The degree requirement [MIT Catalogue] specifies 66 units, which corresponds to 6 graduate level 12-unit subjects. The Requirements for a dual Aerospace-CDO SM degree are given in the appendix (taken from http://web.mit.edu/cdo-program/)

7. Courses related to Aerospace Computational Engineering

Core Computational Subjects

This courses provide the foundation/core material that provides the basis for study of more advanced elective topics. Students pursuing SM and PhD are recommended to take at least two of the following subjects:

- 2.097J/6.339J/16.920J Numerical Methods for Partial Differential Equations

- 2.098J/6.255J/15.093J Optimization Methods

- 6.337J/18.335J Introduction to Numerical Methods

Core Disciplinary Subjects

Students pursuing SM/PhD are recommended to take two/four of the following subjects:

- 1.138J/2.062J/18.376J Wave Propagation

- 2.071 Mechanics of Solid Materials

- 2.072 Mechanics of Continuous Media

- 2.073 Solid Mechanics: Plasticity and Inelastic Deformation

- 2.25 Advanced Fluid Mechanics

- 3.22 Mechanical Properties of Materials

- 16.110 Flight Vehicles Aerodynamics

- 16.120 Compressible Flow

- 16.31 Feedback Control Systems

- 16.511 Aircraft Engines and Gas Turbines

- 16.512 Rocket Propulsion

- HAA6711 Advanced Elasticity

Advanced Computational and Disciplinary Subjects

Students pursuing SM and PhD are recommended to take one or more of the following subjects:

- 2.093 Computer Methods in Dynamics

- 2.094 Finite Element Analysis of Solids and Fluids

- 2.095 Molecular Modeling and Simulation for Mechanics

- 2.27 Turbulent and Separated Flows

- 16.13 Aerodynamics of Viscous Fluids

- 16.225J/2.099J Computational Mechanics of Materials

- 16.540 Internal Flows in Turbomachines

- 16.888J/ESD.77J Multidisciplinary System Design Optimization

- 16.930 Advanced Topics in Numerical Methods for Partial Differential Equations

Other Recommended Subjects

The following subjects provide breadth in computation or in other aerospace-related disciplines:

- 1.128J/2.089J/16.940J Computational Geometry

- 2.036J/18.385J Nonlinear Dynamics and Chaos

- 2.096J/6.336J/16.910J Introduction to Numerical Simulation

- 2.798J/3.971J/6.524J/10.537J/20.410J Molecular, Cellular, and Tissue Biomechanics

- 3.320 Atomistic Computer Modeling of Materials

- 6.231 Dynamic Programming and Stochastic Control

- 6.251J/15.081J Introduction to Mathematical Programming

- 6.252J/15.084J Nonlinear Programming

- 6.338J/18.337J Parallel Computing

- 18.306 Advanced Partial Differential Equations with Applications

- 18.307 Integral Equations

- 18.336 Numerical Methods for Partial Differential Equations

8. Faculty and Staff with Interests in Aerospace Computational Engineering

Darmofal, David (Prof.) (darmofal@mit.edu)

Drela, Mark (Prof.) (drela@mit.edu)

Haimes, Robert (haimes@mit.edu)

Peraire, Jaime (Prof.) (peraire@mit.edu)

Radovitzky, Raul (Prof.) (rapa@mit.edu)

Willcox, Karen (Prof.) (kwillcox@mit.edu)

Please consult MIT Aero & Astro web-page for detailed faculty and staff interests:
http://web.mit.edu/aeroastro/faculty/faculty.html

APPENDIX - Admission to the MIT CDO Program

Rolling Admission for Current MIT Graduate Students

The CDO Program will accept applications on a rolling basis from current MIT graduate students who wish to pursue the CDO Master's degree concurrent with their existing degree program. Students must be enrolled in a departmental S.M. or Ph.D. degree-granting program to be considered for admission on a rolling basis.

Students Pursuing Dual MIT Degrees

Dual SM Degrees

Students who are pursuing the CDO Master's degree concurrent with another MIT Master's program will need to satisfy the course requirements for both degree programs. These students must complete (in addition to thesis units) at least 132 subject units. In principle, the same Master's thesis can be used to satisfy both degrees, provided the thesis topic is approved by the CDO Steering Committee and by the MIT Department granting the other Master's degree. In those cases where the thesis advisor is not a CDO-affiliated faculty member, there should be a CDO-affiliated faculty member who acts as a thesis reader.

Dual SM/PhD Degrees

Students who are pursuing the CDO Master of Science degree concurrent with an MIT PhD program will need to satisfy the course requirements for both degree programs. A separate thesis for each program is required to satisfy the CDO Master's and PhD program requirements.

In those cases where the CDO Master's thesis advisor is not a CDO affiliated faculty member, there should be a CDO affiliated faculty member who acts as a thesis reader. For February admission (spring term) to the CDO Master's program, applications are accepted on a rolling basis from September to the end of December. For September admission (fall term) to the CDO Master's program, applications are accepted on a rolling basis from January to the end of April.