A Modern Approach to Graduate Flight Dynamics, Stability, and Control Courses

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The Aerospace Industry is about to lose a large body of experienced engineers to retirement in the next one to five years. With an experienced but relatively small group of engineers in the 10-15 years experience range, corporations will soon find themselves increasingly forced to rely upon a very young engineering work force. It is critical that these young and talented engineers be able to analyze complex, highly integrated modern air vehicle systems. To adequately respond to this need, universities must not exclusively teach the traditional engineering fundamentals. Rather, they must focus on producing graduates who have been exposed to modern flight vehicle characteristic, and are well trained in modern analysis techniques. This paper proposes in detail a course intended to be responsive to the current and future needs of the Aero Industry. By fusing the combined experience and knowledge of an academician and a practicing engineer, a modern graduate level course in flight dynamics, stability, and control is outlined, featuring a balance of theory, computation, and experiment. Desired student outcomes, pedagogy, and specific topics and focus areas are proposed and discussed.

An unrelated but no less significant problem is the relevancy of the traditional flight mechanics texts. The methods presented in these standard texts, and the texts themselves, all date to the late 1970's. The general type of configurations to which these texts are applicable is shown in Figure 1. More recent configurations possess significantly different features which have a pronounced effect on stability and control, such as chined forebodies, serrated trailing edges, and unusual fuselage cross sections (Figure 2). Although aircraft such as the SR-71 possessed some of these features as far back as 40 years...
ago, the point is that these features are almost commonplace today.

Numerical methods of all kinds have made tremendous strides in the intervening years too. In addition to the well publicized advances in Computational Fluid Dynamics (CFD), the area of fluid/structure interaction, and in particular aeroelasticity, has experienced significant advances. An improving capability to analyze highly nonlinear aeroelastic problems, such as the decades old problem of wing store flutter in high performance fighter aircraft, is opening a door previously shut to graduate level flight dynamics, stability, and control courses.

All of the above provide a strong indicator of the need for a modern, i.e. updated, graduate level course in flight dynamics, stability, and control. A previous paper proposed topics and a methodology for teaching a modern undergraduate course in this field\(^1\). The present paper extends some of these earlier concepts by first proposing desired outcomes and pedagogy, and then methodologies and content which the authors believe are relevant for a graduate level understanding of the subject. The recommendations and ideas herein stem entirely from the authors' experiences in industry and academia, and are not intended to be all-encompassing and all-inclusive. It is also acknowledged that some features might already be included in existing graduate courses at some universities. Finally, it is not the authors' intent to provide an exhaustive bibliography of all available stability and control texts and reports. Thus, omissions do not indicate an opinion on the merit or lack thereof of particular texts or reports.

**Desired Student Outcomes**

Because of the strong industrial flavor, the course is primarily targeted to Master of Science level students who plan to work in industry, or who are returning to school from industry. However, Ph.D. level students will find it a good compliment to more theoretical courses. Considering the target group, the desired student outcomes of the proposed modern graduate level course on stability and control are:

- complete grasp of underlying theory
- working knowledge of the mathematics which support underlying theory
- practitioner level proficiency with software analysis tools, both in coding of original algorithms and usage of existing codes
- experience with designing and executing experiments
- an understanding of the interplay and relationships between all of the above

In general, effective evaluation and assessment of desired outcomes is difficult at best, particularly at the graduate level. While the authors recognize its importance, it is beyond the scope of the present paper except for the following: if upon completion of this type of course a student is able to successfully (and with much insight) analyze the characteristics of a modern flight vehicle through analysis, simulation, and experimentation, then the overall desired outcome is achieved.
Pedagogy

The pedagogical paradigm for the proposed course is "Give them the knowledge, and the tools, and the big picture". This paradigm demands a balance of theory, computation, and experiment for specific relevant topics. This in effect a bridging of the gap between a pure theory graduate course, and a pure experimental course. Although this idea is not at all new, the pervasiveness of the bridging (integration among all aspects), is new. For example, instead of several analytically rigorous homework assignments on stand-alone topics, there should be fewer assignments (perhaps a total of four for a semester based course) of a more integrated, case study nature. Ideally, the topic of these case study modules would be supplied by industry. Each case study homework module would require use of the following methods and aspects:

- analytical
- numerical
- experimental
- design

Suggested analytical and numerical methods are discussed in following sections, but the experimental methods and design aspects are discussed here. As many in academia know, at least as much student learning often occurs from simply designing an experiment, as it does from analyzing the results of an experiment. A fundamental understanding of Modern Design of Experiment techniques is crucial when considering an experiment\textsuperscript{7, 8}. Student understanding of the interplay between stability and control and preliminary design is crucial. The usual dichotomy is that size, location, configuration and (in the case of effectors) actuation for the purpose of stability and control can be at odds with mission performance, e.g. low observables, weight, manufacturability, maintainability, and cost considerations. A key feature of this pedagogy is a close tie with industry, including guest lecturers for specific topics. Industrial quality software and analysis tools should be used, but only where appropriate. This is because antiquated legacy codes exist which in many cases have much capability, but are difficult and time consuming to learn, and non user friendly. The capstone of the course would be a comprehensive final project including all of the factors mentioned above, of a topic supplied by industry, and which is (ideally) presented to industry in both oral and written form. This comprehensive final project model is in widespread use in preliminary design courses (many of which are not aerospace in nature), but is novel by comparison to the traditional analytically heavy graduate course model.

Selected Major Topics

A detailed list of twelve proposed topics intended to accomplish the desired student outcomes is presented below. The order of presentation is not ranked by importance, but rather by the general sequence in which the methods are actually used in a new aircraft program: requirements definition, conceptual, preliminary, final.

I. Flying and Handling Qualities Requirements

The flight dynamics engineer should be familiar with the standard aircraft flying qualities requirements presented in MIL-F-8785C, MIL-STD-1797, and FAR Part 23, etc. These documents and the attendant users guidelines provide important lessons-learned and guide stability & control and flight control system design for all aircraft from the conceptual design phase through flight testing. The student should also be exposed to handling qualities testing and analysis, handling qualities ratings, and pilot induced oscillations (PIO). Reference 2 is a good source for background information. The student should also be exposed to special high angle-of-attack (AOA) problems (both upright and inverted) including post stall gyrations and spins, deep stall, and falling leaf.

II. Conceptual Design for Flying Qualities

The stability & control engineer is often the first individual from the Flight Dynamics organization to become involved in a new aircraft design. This typically occurs during the earliest conceptual design stage when wing planform, configuration layout and control surface sizes are determined. During this stage, first-order approximations are most applicable to determine center-of-gravity limits, high AOA departure susceptibility, roll performance, longitudinal and lateral/directional trim characteristics.
IV. Flight Testing and Vehicle Validation

Approximations of flight control actuator rate requirements and the effects of higher-order non-linear effects must also be considered\(^4\).\(^5\).\(^6\). For these reasons, a rudimentary six-degree-of-freedom (6-DOF) simulation is invaluable during the conceptual design stage. Students should be familiar with what factors determine control power requirements for both conventional and statically unstable aircraft.

The flight dynamics engineer is also required to be knowledgeable of various aerodynamic prediction methods ranging from low-order vortex lattice methods, to higher order Euler or Navier-Stokes routines. Small scale, low-speed wind tunnel testing is also required at the earliest stage in order to estimate high AOA characteristics and nonlinear aerodynamic effects. Data from both analytical methods and the small-scale tests will form the basis of early simulations.

III. Introduction to Wind Tunnel Test Techniques and Aerodynamic Math Models

As the configuration matures, larger scale wind tunnel testing is undertaken using more expensive models and tunnels. Dynamic testing using rotary balance and forced oscillation test rigs is also important during this stage. The time spent during the previous design effort in the small-scale wind tunnel will result in considerable savings as large-scale wind tunnel models and test time can run into the tens or even hundreds of millions of dollars during configuration development. As data are collected, a high-fidelity aerodynamic simulation database is compiled and the 6-DOF simulation becomes more detailed. Sensor dynamics, high-order actuator dynamics and detailed structural flexibility effects are modeled. The simulation model becomes the basis for a pilot-in-the-loop simulation where preliminary handling qualities experiments and flight test planning is performed. Knowledge of how the aerodynamic data are collected, analyzed and integrated into the simulation math model are critical to understanding the usefulness and limitations of high-fidelity simulations.

Together with the subject of wind tunnel testing, the student needs to have a sound background in statistics. A fundamental understanding of Modern Design of Experiment techniques and their application to aerospace vehicle design is also helpful\(^7\).\(^8\).

IV. Flight Testing and Vehicle Validation

Finally, as the configuration lines are frozen, attention should begin to shift to flight test planning and execution. Planning for the test program should include not only flying qualities verification, but also aerodynamic validation using parameter identification (PID) methods. Students should be exposed to these analysis methods. Today’s most modern methods utilize frequency domain techniques\(^9\).\(^10\). Successful application of PID methods requires careful up-front planning long before the vehicle first flies. Test configurations, maneuver design, data acquisition methods and post processing of the data are just four of the important factors that must be considered during flight test planning. Ad-hoc application of PID methods after a flight test program has begun are almost certainly doomed to fail. Poor attention to detail will result in schedule delays and severe cost over-runs during the flight program. The student must be cognizant of the decisions made throughout the flight test planning phase and how they can directly impact the success or failure of the program.

V. Dynamics

The emphasis here is on nonlinear dynamics since it is assumed that the prerequisite undergraduate course primarily uses linearized equations of motion and related analyses, and because many problems of interest are highly nonlinear in nature (high alpha\(^11\), fighter agility\(^12\)-\(^15\), etc.). Besides Newton’s 2\(^{nd}\) Law, deriving equations of motion using the Lagrangian method and D’Alembert’s principle are very useful in aerospace applications. The latter is especially useful for multi-body systems with constraints. Presentation of how to derive equations of motion for arbitrary centers of mass (as is often done in spacecraft applications) is strongly recommended. The nonlinear approach necessarily requires Lyapunov and phase-plane methods to analyze stability. Numerical methods are required to analyze the transient behavior of nonlinear systems, and to analyze the stability of nonlinear systems that do not apply to Lyapunov analysis.

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VI. Reference Frames and Coordinate Transformations
The student should be familiar with the various aircraft axes systems used in flight dynamics and their applications: (1) the body axis system; (2) the stability axis system; (3) the primed stability axis system; and (4) the wind axis system. Wind tunnel data are typically collected and presented in the body and/or the stability axis system; lateral-directional aerodynamics are usually easier to visualize and understand in the body axis. Oftentimes, flight and wind tunnel data are presented in stability axis. This axis system is most often used to understand the airframe stability characteristics and lateral-directional controllability. Lateral-directional analysis is usually performed using the primed stability axis system -- the primed axis system provides a methodology that results in decoupling the inertia terms in the lateral and directional axes. Finally, high AOA dynamic data are often analyzed in the wind axis system.

Furthermore, extension of the equations of motion to multi-body systems naturally leads to multiple reference frames. This in turn requires knowledge of and familiarity with relative velocities and accelerations. In terms of coordinate transformations, students should learn quaternions, Rodriguez Parameters, and Modified Rodriguez Parameters.

VII. Modal Analysis
Undergraduate courses usually focus on eigenvalues, eigenvectors, and mode shapes. The modal analysis proposed here is modal superposition. Reference 18 demonstrates how to construct and interpret linear models in terms of a modal vector, not a state vector. This allows one to see the effect each control input has on specific modes, not just the states.

VIII. Elastic Effects
This topic covers the effects of body bending, or structural flexibility. Airframe flexure causes additional aerodynamic loads that in turn cause additional flexure. At a basic level, aeroelastic effects influence the rigid body aerodynamics through reductions in bare airframe stability and control power. In a dynamical sense, interactions occur between the elastic modes and the flight control system as it senses both the rigid body motions and the elastic motions. Again, frequency domain methods and parameter identification methods have application here. Topics include methods for determining the natural frequencies and modal shapes of the body bending modes, and methods to account for fuel slosh. Students should be exposed to the importance of aero-servo elastic interactions and how they are handled in the design and testing of the flight control system.

IX. Atmospheric Effects
This is the study of the effects of gusts and turbulence on the airframe and the resulting effect on flying qualities. For gusts this means deriving transfer functions that relate airframe outputs to various gust inputs, such as the response of angle-of-attack to a vertical gust input. Also of importance is the response of the aircraft to random-type inputs. These would consist of atmospheric turbulence, terrain elevation, and noisy sensors. Aircraft flying in turbulence can be subjected to excessive g-loads. Flutter, the condition essentially characterized by structural damping going to zero, is another consideration. Exposure to analytical methods for predicting the performance of the system to random inputs is required in all of these situations. Study of the theory of random processes is required.

X. Spinning Rotors and Mass Imbalance
This subject would cover the study of angular momentum in-depth and in three dimensions, leading to gyroscopic effects due to spinning rotors, and the effects of rotating mass imbalance which lead to vibrations at high angular velocities. The effects of asymmetric mass distributions due to hung stores or airframe damage are also to be considered.

XI. Inertial and Kinematic Coupling
The familiar cross-coupling in aircraft is due to an imbalance in the magnitudes of the inertia terms in the rotational equations of motion, and can be induced by perturbations in any of the body-axis angular rates. The specific phenomenon of roll coupling is an important subset. A method to analyze and define specific boundaries in terms of aircraft parameters is presented in references 3, 6 and 19. Additionally, the kinematic coupling between AOA and sideslip are of paramount importance during rolls at high AOA.
XII. Mathematics

The mathematical tools for the course, both analytical and numerical method based, would likely be a combination of pre- and co-requisites:

- linear algebra, including abstract vector spaces
- linear system theory
- describing functions
- phase-plane analysis
- bifurcation methods and chaos theory
- numerical methods using least squares, splines, and basis functions
- functions of a complex variable
- probability, random variables, and random processes

Summary and Conclusions

This paper introduced the motivation and outline for a modern graduate course in flight dynamics, stability, and control which attempts to be responsive to the current and future needs of the aero industry. Desired student outcomes and a pedagogy were presented, along with twelve specific topics and math pre/co-requisites relevant to a graduate level command of the subject. It is acknowledged that adoption of the proposed pedagogy, tools, and topics is subject to instructor preference and interpretation, in addition to the preparedness and prerequisites of the students. Although full adoption would be ideal, it is concluded that adoption of most of the proposed pedagogy, tools, and topics would likely be an improvement, if the objective is to be more responsive to the current and future needs of the aero industry.

Statement

The opinions expressed in this paper are those of the authors, and not necessarily those of Texas A&M University, and Lockheed Martin Aeronautics Company.

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