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An Eclectic Approach to Undergraduate Flight Dynamics, Stability, and Control Education
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AN ECLECTIC APPROACH TO UNDERGRADUATE FLIGHT DYNAMICS, STABILITY, AND CONTROL EDUCATION

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Abstract
The subject of airplane flight dynamics, stability, and control is generally recognized to be interdisciplinary in nature. A deficiency exists in undergraduate flight dynamics, stability, and control education because this course is traditionally taught with a relatively narrow, analytical focus. Additionally, no one textbook thoroughly addresses this deficiency. This paper proposes an eclectic approach to teaching this subject where the inter-relationships of flight dynamics, stability, and control with other disciplines are emphasized. By utilizing the best material from several different sources, the topics are unified to present a total picture of the discipline. This approach not only enhances the student learning experience and makes the course more interesting, it also helps with the retention of material. Suggestions on which aspects and topics to include are presented, along with specific examples of how to implement these ideas in the classroom.

Introduction
With the exception of airplane design, the subject of airplane flight dynamics, stability, and control is possibly the most interdisciplinary field in aeronautical engineering. The subject of airplane flight dynamics, stability, and control is concerned with the reaction of the airplane to externally (turbulence and upset gusts) or internally (e.g., changes in control surface deflection, e.g. location, and configuration) generated disturbances. Manned aircraft must be designed so that a human pilot can fly a mission and maneuver it without undue effect, with or without assistance from an automatic control system. Civilian and military operators translate this last statement into detailed specifications for flying qualities. For all of these reasons stability and control is highly interrelated to performance, flight dynamics, and aeroelasticity.

Roskam relates in Reference 1 that from the beginning of manned flight, the subject of flight dynamics has been subdivided into three main areas: performance, stability and control, and aeroelasticity (Figure 1). Until about 1950, these three areas were considered to be largely independent of each other. Since then, it was found necessary to re-structure this classification to account for structural deformations due to aerodynamic loads, and aeroelastic effects on stability and control. A revised structure is displayed in Figure 2.

The practicing flight dynamicist requires intensive training in several branches of engineering science, and a broad outlook insofar as the practical ramifications of his work are concerned. Despite recognition of the interdisciplinary nature of flight dynamics, stability, and control in the university setting, the perception is all too often that it should be taught as a distinct, stand alone subject. Although the classification scheme exemplified by Figure 2 clearly indicates relationships according to broad discipline, it does not provide specific information as to the fields and topics which are best suited to teaching this subject at the undergraduate level. To provide students with a complete understanding and rigorous background of the subject, a classification scheme due to Etkin in Reference 2 is helpful (Figure 3). This subdivision is useful both from the standpoint of the technical problems associated with different motions, and of the formulation of their analysis.

Aerodynamics and performance have typically been the areas most emphasized in courses on flight dynamics, stability, and control. The important effects and implications of aircraft
design and operation, the pilot/airframe as a combined system, flight control, and even propulsion are too often left by the wayside. This is probably due more to the background of the individuals who actually teach the courses than any intended omission. In this context familiar disciplines and experiences naturally tend to be emphasized more than others. Ideally, the airplane flight dynamics, stability, and control instructor should be capable of wearing many hats. Practical considerations and department faculty demographics prevent this in all cases. Compounding this situation is the fact that no single textbook exists today which fully integrates these disciplines into a course on airplane flight dynamics, stability, and control. It is unreasonable, however, to expect a single text to possess all of the coverage to the degree that this paper advocates. An eclectic approach is therefore proposed as one solution to this problem.

This paper proposes an eclectic approach to teaching undergraduate flight dynamics, stability, and control. It demonstrates how to effectively integrate the approach into a classroom learning experience. The intention is not a complete scrapping of existing course structures, but rather a fine tuning. Therefore, instead of proposing a revised topic list, this paper recommends certain aspects and disciplines be emphasized and included in existing course structures. Examples of incorporating these additional aspects into a course are presented.

Elements of the Eclectic Approach
The eclectic approach consists of the following ten elements. All ten elements should be incorporated to a greater or lesser degree. The list below is based loosely on order of importance.

1. HAVE A SPECIFIC OVERALL COURSE OBJECTIVE
A specific overall course objective is essential for a rewarding student experience. However, having an objective is not an end to itself. How you get there is just as important as where you are going! Many airplane design aspects can easily be incorporated into the course. Instead of just pure analysis, it is suggested to set airplane design as the specific, overall course goal. The ramifications is that most course topics will now have a definite design slant (which in fact they do anyway!). Emphasizing the impact of stability and control on the aircraft design process will make for an enjoyable student learning experience. It will also build the necessary analytical skills, tools, and insights which will come in handy later in a capstone airplane design course.

2. REAL WORLD
Relate everything to the "real world" as much as possible! Don't just talk about a particular aspect of stability and control, use a specific example of the peculiarities, problems, and fixes required of real aircraft. Also encourage or test students to visually identify classic and modern aircraft. All of this enhances retention by linking concepts taught in class to tangible objects. An example is the variation of rolling moment coefficient due to perturbation in sideslip angle (\( C_{10} \)). After presentation and discussion of this stability derivative in the classroom (including contributions due to position of wing on the fuselage, leading edge sweep angle, and dihedral angle), an exam question was posed which combines all of these elements (Figure 4).

3. WHERE DOES THE DATA COME FROM?
Stability and control data comes from sources such as wind tunnels, analytical studies, and flight tests. Stress this relationship throughout the course as the wind tunnel data and flight test data often get overlooked. Students should be exposed to real data to see how "dirty" and corrupted it can be. Some textbooks such as Reference 3 contain wind tunnel data to be analyzed by the student. Examples of actual flight test data for parameter identification can be obtained from sources such as Reference 4. Flight test data and interpretation of stability and control results can be obtained from sources such as References 5 and 6.

4. REGULATIONS AND SAFETY
Performance is probably the strongest, most traditional link to stability and control. However, safety is eclipsing performance as a prime concern in the industry these days:

"The safety record of the world's airlines will decline in the next 20 years unless the industry focuses more on preventing accidents than determining what
caused them, according to a study conducted by the Boeing Commercial Airplane Group."
(Reference 7)

Students must be exposed to safety regulations such as one engine inoperative (OEI), takeoff rotation, stick force-to-speed gradient, etc. at an early stage. Requiring students to be familiar with major FAA and Military regulations instills safety where safety should start: with the people who design and build the aircraft. Additionally,

"In 1994 nearly 1,300 passengers and crew were killed in civil aircraft accidents. The problem for the aircraft and systems industry is that while they can develop specific systems to counter specific dangers, their role in solving problems associated with the complex issue of human/machine interface is still hazy." (Reference 8)

Not only flying qualities, but some human factors too, including the effects of displays and pilot cues. Many systems now help the pilot close the loop, but keeping track of augmented flight modes and their effect on the vehicle is a concern.

5. ECONOMICS AND MARKETING
The aerospace industry is influenced largely by economic and marketing considerations. This translates into knowing who the user is and what his needs are. These users or customers are the military, commercial, and civilian sectors. Each sector imposes their own unique needs and therefore requirements and flying qualities for the aircraft they use. Introduce and highlight the aspects of these "facts of life" to prepare students for their careers.

6. ETHICS AND PROFESSIONAL RESPONSIBILITY
This should be an aspect of every course in the engineering curriculum. Although perceived as a natural or inherent understanding, engineering ethics must be taught. Professional registration goes hand-in-hand with ethics. Today more than ever before engineering responsibility needs to be promoted because of public sensitivity to environmental issues such as aircraft noise, excessive fuel dumping during operations, and ozone layer depletion. These issues have a tremendous impact on the industry. References 9 and 10 are highly recommended.

7. WHERE WE HAVE BEEN AND WHERE WE ARE GOING
Know something about your profession! An excellent article on the history and development of airplane flight dynamics, stability, and control is by Roskam in Reference 11. Another is the history of the variable stability airplane by Breuhaus in Reference 12. Anderson provides a wealth of aviation and aeronautical engineering history in his textbooks, e.g. References 13 and 14. Students naturally tend to wonder how flight dynamics, stability, and control are being used today, and in the future. Fighter agility metrics is a popular and well documented application which should continue to see use in the near future. References 15-18 are recommended.

8. KEEP CURRENT
The need to be aware of current progress and trends is mandatory for success in the engineering profession. Students should get into this habit now, by reading the weekly and monthly aviation magazines, in addition to professional journals.

9. WHAT BOOKS TO USE?
This is largely a matter of preference. The only definitive statement to be made here is that one single textbook will usually not suffice if the instructor intends to present "the larger picture" of the subject. A combination of References 2, 3, 19-26 are recommended. Note that not all of them are "pure" airplane flight dynamics, stability, and control texts!

10. MULTI-MEDIA
Today, there are many ways to analyze data than simply by hand. Once calculations have been learned by hand, software tools such as Advanced Aircraft Analysis (AAA) (Reference 27), and VORSTAB (Reference 28) are useful for assisting students with the more tedious calculations. They are also excellent preparation for airplane design. The MATLAB software (Reference 29) is useful for generating and analyzing transfer functions, dynamic modes, and
time histories. These software tools are also relevant with regard to regulations. Rotations and gyrations of the human hand and airplanes mounted on a stick are of limited effectiveness in teaching flight dynamics to students. Video tapes are a popular and effective way to reinforce the topics learned in class. Besides being entertaining, many have significant engineering content which makes them suitable for classroom use.

**An Example**

Appendix A contains a detailed example of the eclectic approach applied to the phugoid and short period longitudinal dynamic modes.

**Putting it All Together**

At first glance it might appear that integrating items 1 through 10 above into a single course is an invitation to disaster. When carefully structured, this can be avoided. What follows is one example of how the eclectic approach has been implemented. At Western Michigan University AE 460 Aircraft Stability and Control is a three credit hour course (three one-hour lectures per week), structured as follows:

<table>
<thead>
<tr>
<th>component</th>
<th>percent of total student grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homework (weekly)</td>
<td>15</td>
</tr>
<tr>
<td>Quizzes (weekly)</td>
<td>5</td>
</tr>
<tr>
<td>Midterms (3)</td>
<td>20 each</td>
</tr>
<tr>
<td>Final Exam</td>
<td>20</td>
</tr>
</tbody>
</table>

The primary textbook is Reference 3. Other books used by both the instructor and recommended to students during the course are:

i) texts in analytical methods for stability and control calculations (e.g., Reference 30)

ii) a text in flight test engineering (Reference 24)

iii) three additional texts in aircraft stability and control (References 2, 21, and 23)

iv) aircraft data base and recognition resources (References 31, 32)

**Continuity Across Courses**

The engineering prerequisites for AE 460 are AE 361 Flight Vehicle Aerodynamics; ME 356 Fluid Mechanics; and ME 360 Control Systems. Math prerequisites are differential equations and linear algebra. Co-requisites are AE 450 Flight Vehicle Performance; AE 463 Aircraft Structural Design; and AE 466 Aeronautical Propulsion Systems. Armed with this knowledge, the next semester students take AE 469 Aircraft Design, and AE 459 Flight Test Engineering and Design. The payoff is realized in the Aircraft Design course since the students are already familiar with the major regulations, and are conscious of safety from the first day of class. In addition, students are able to devote the majority of their efforts to learning preliminary design. The time consuming stability and control analyses required for aircraft design are learned in the previous course.

How well does the proposed approach work in practice? The following are student responses:

"The course was a little different than I expected, though it turned out better than I thought it would. The many three-views and handouts were particularly interesting and useful."

"The use of practical problems and examples makes the class more interesting. The instructor did an adequate job of making us understand the federal and military regulations, (control) surfaces, and flight control."

"The use of the 3-views helped in showing the different designs of planes and why the designs are the way they are."

**Summary and Conclusions**

An eclectic approach to teaching undergraduate flight dynamics, stability, and control is proposed. Selection of a course objective and other important aspects for a complete treatment of the subject have been addressed. Ten specific factors relevant to engineering issues have also been identified. Although the order of inclusion and relative importance of these factors is subject to personal preference and interpretation, it is recommended that all nine be incorporated in the course.
Acknowledgments
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References


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Figure 1 Early Classification of Stability and Control Disciplines (Reference 1)

Figure 2 Post 1950 Classification Scheme (Reference 1)

Figure 3 Full Interdisciplinary Classification Scheme (Reference 2)
6. (25 points) The questions below pertain to the non-dimensional stability derivative $C_{1\beta}$.

a) What is the name of this derivative, its definition, and its sign for a statically stable airplane?

b) Identify by manufacturer, designation, and name the aircraft shown below.

c) Discuss both the magnitude and sign of $C_{1\beta}$ for this aircraft in terms of specific parts of the configuration, using what you have learned this semester.

d) Discuss the implication of the chosen wing location from the design and the operational points of view.

Figure 4 Sample Exam Question Containing "Real World" Aspects
Appendix A

Example of Eclectic Approach Applied to Short Period and Phugoid Modes

a) Starting with the following longitudinal transfer functions, due to Nelson in Reference 19:

\[
\frac{u}{\delta_e}(S) = \frac{A_u S^3 + B_u S^2 + C_u S + D_u}{A S^4 + B S^3 + C S^2 + D S + E}
\]

\[
\frac{\alpha}{\delta_e}(S) = \frac{A_\alpha S^3 + B_\alpha S^2 + C_\alpha S + D_\alpha}{A S^4 + B S^3 + C S^2 + D S + E}
\]

Coefficients are functions of the longitudinal stability derivatives. Roots of denominator of transfer functions (characteristic equation roots) indicate the presence of two second-order modes. One mode (phugoid) has low undamped natural frequency and low damping ratio, the other (short period) has an undamped natural frequency of approximately one order of magnitude greater, and larger damping ratio.

b) Frequency response of \(u/\delta_e\) and \(\alpha/\delta_e\) transfer functions, due to Blakelock in Reference 26:

Frequency responses indicate that Phugoid mode is exhibited mainly in perturbed airspeed response, while short period mode is exhibited mainly in perturbed angle-of-attack response.
c) Simulation time histories of the phugoid and short period modes, due to Ward in Reference 24:

Time histories confirm part b) above, in that phugoid mode is exhibited in perturbed airspeed, short period is exhibited in perturbed angle-of-attack. Both modes are discernable in a response to an elevator input.

d) Approximation of phugoid undamped natural frequency and damping ratio from assumption of constant angle-of-attack, including design implications, due to Roskam in Reference 3:

\[ \omega_{\text{ph}} = \frac{g}{U_1} \sqrt{2} ; \quad \zeta_{\text{ph}} = \frac{\sqrt{2}}{2 \left( C_{L_1} / C_{D_1} \right)} \]

Phugoid undamped natural frequency is independent of airplane configuration, but is inversely proportional to steady-state airspeed. Phugoid damping ratio is inversely proportional to the airplane lift-to-drag ratio, i.e. airplanes with large L/D typically have poor phugoid damping.

e) Pilot considerations of the phugoid and short period modes, due to Ward in Reference 24:

"The pilot's inputs are made often enough that he usually can control a divergent phugoid and not even be aware of this long term instability. Such handling qualities often occur when the airplane is configured for landing (called the power approach (PA) configuration). The short period oscillation is consequently of greater importance as far as dynamic response is concerned because the pilot must control it immediately if it is not well-damped. If his reactions are too slow or are phased improperly, his commands may even drive the closed-loop system unstable. Of course, the dynamics of the control system itself may hamper or even preclude the pilot from making appropriate corrections."