A Flexible, Problem-Based, Integrated Aerospace Engineering Curriculum

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Abstract – **The paper describes a flexible, problem-based approach to integrating engineering courses. Students work in teams to identify, research, and study a current problem that involves applications from each of the courses involved. Two pairs of aerospace engineering courses were used to demonstrate the feasibility and effectiveness of this idea: (a) aerodynamics and flight mechanics, and (b) compressible flow and aerospace propulsion. The courses in each pair lend themselves easily to integration because one sets the foundation for applications in the other. This approach offers undergraduates an opportunity to engage in research under the supervision of two or more faculty members, while addressing almost all the outcomes of ABET Criterion 3. It is also flexible, so it can be expanded to allow integration of material from any number of courses. The paper discusses the rationale, process, and benefits of integrating engineering courses through projects, provides specific examples of such projects, and presents a rubric for evaluating student performance.**

Index Terms – Undergraduate research experiences, integrated curricula, problem-based / learning.

INTRODUCTION

Engineers by definition are problem solvers. Whether they are involved in analytical, experimental, computational or design work, engineers solve problems. Yet, real world problems tend to be quite different from most exercises found in engineering texts. While these exercises make an important first step in helping students bridge the gap between theory and application, they do not provide the complexity and depth necessary to master problem-solving skills. Many studies have found that engineering graduates, even though they solve more than 2,500 exercises in their undergraduate work, lack the essential problem-solving skills needed to tackle real world problems [1]. Woods et al [1] give a comprehensive list of problem-solving skills from both the cognitive as well as the affective domain, while Mourtos et al [2] present example open-ended engineering problems, designed to help students master such skills.

A second problem with traditional engineering curricula is the compartmentalization resulting from course-focused education. As Bordogna et al [3] point out *engineering is an integrative process and thus engineering education, particularly at the baccalaureate level, should be designed toward that end.* They recommend *a more holistic approach in which process and knowledge are woven throughout the curriculum* [3]. Hence, connecting the parts is an important element of an effective engineering education.

Several engineering schools addressed this problem with integrated curricula in the 1990s [4]-[9]. This integration takes place primarily in the first two years and offers two great advantages over traditional curricula:

a. It provides students with the engineering context for studying mathematics and science.
b. It gives freshmen a realistic and positive orientation to the engineering profession through engaging, hands-on, design projects.
c. The increased communication among the faculty who design and teach these courses, helps them understand better the connections between each other's disciplines.

On the other hand, this kind of large-scale integration requires students to register for a multi-unit course or set of courses, which brings together calculus, physics and / or chemistry, graphics, freshman engineering, and sometimes a communications or other humanities subject. This approach does not work well in schools where (a) students work part-time, hence they cannot register for an integrated course that amounts to almost a full-time load, and (b) a large percentage of students do not pass the placement tests for calculus, physics or chemistry, hence they do not qualify for integrated courses. Moreover, the positive effects mentioned above are limited to the first two years of engineering study; the problem of compartmentalization still remains for upper division engineering courses.

An additional characteristic of modern, real world problems is their multidisciplinary nature. For example, engineers who design aerospace systems often integrate knowledge of:

- Traditional aerospace engineering disciplines (ex. aerodynamics, flight mechanics, aerospace structures, stability and control).
- Other engineering disciplines (ex. mechanical design, electrical and power, environmental, manufacturing, reliability, maintainability).
- Non-engineering disciplines (ex. economics and marketing).

This paper describes a flexible, problem-based approach to integrating engineering courses, which offers students opportunities to identify, formulate, and solve multidisciplinary engineering problems.

PROBLEM-BASED INTEGRATION

In their junior and senior years, SJSU aerospace engineering (AE) students follow closely a set of prescribed courses, as part of their four-year graduation plan. Each term their schedule includes at least three AE courses as shown in Table I. Courses shown in italics are offered every semester. The remaining (not shown in Table I) are general education courses. In each of these courses, students are given the choice to work in teams on an integrated, multidisciplinary project for substantial course credit (20-30 %). In some courses students are given the option to do the project in lieu of the final exam.

TABLE I
JUNIOR AND SENIOR LEVEL COURSES
FOR POSSIBLE PROBLEM-BASED INTEGRATION

Spring (Junior Year)
ME130 Applied Engineering Analysis – Required Course
AE114 Aerospace Structures – Required Course
AE140 Rigid Body Dynamics – Required Course
AE162 Aerodynamics – Required Course
AE165 Flight Mechanics – Required Course
Fall (Senior Year)
ME120 Experimental Methods – Required Course
AE110 Space Systems Engineering – Capstone Course for Space Systems Option
AE164 Compressible Flow – Required Course
AE167 Aerospace Propulsion – Required Course
AE170A Aerospace Vehicle I – Required Senior Design Course
Spring (senior Year)
ME147 – Dynamic Systems Vibration & Control
AE168 Stability & Control – Capstone Course for Aircraft Design Option
AE169 Computational Fluid Dynamics – Capstone Course for Space Transportation & Exploration Option
Technical Elective Courses (2)
AE170B Aerospace Vehicle II – Required Senior Design Course

Problem-based integration of two or more courses helps students develop critical skills in almost all of the areas described by the eleven outcomes of ABET Criterion 3 [10], as shown below:

Outcomes 3d (team skills), 3g (communication skills), and 3i (lifelong learning): Students work in teams to choose a problem of interest to them that integrates applications from at least two courses they are taking in the current semester. They research their problem and write a two-page proposal, due on the third week of the semester. The proposal includes a description of the problem, its practical applications and importance, the objectives of the research, the approach to analyze the problem, and a timeline for completion by the end of the semester. Students perform a literature search and consult several references, which they summarize in their proposal. To analyze their problem, they often study material that is not explicitly discussed in any of the courses. Progress reports are due every two weeks throughout the semester. These reports include calculations and intermediate results pertaining to the material of each course. They are graded by the instructor of each course and returned with feedback to the students. A final report and an oral presentation are expected at the end of the semester.

Outcomes 3a (ability to use mathematics, science, and engineering), 3e (ability to identify, formulate, and solve engineering problems), and 3k (modern tools): Students first describe the problem in general terms. Subsequently they define it in engineering terms with specific technical objectives. A mathematical analysis / modeling of the problem is required, and it usually involves the use of commercially available software (see examples below).

Outcomes 3b (ability to design and conduct experiments, analyze and interpret data) and 3c (ability to design a system or component, to meet desired needs within realistic constraints): Students often design and perform experiments to analyze various aspects of their problem. Moreover, the project may involve the design of an artifact (ex. airfoil, wing, airplane or engine inlet) subject to certain constraints.

Outcomes 3h (understanding the impact of engineering solutions in a global and societal context) and 3j (contemporary issues): Students are encouraged to select engineering problems that involve contemporary global and societal issues.

PROBLEM-SOLVING METHODOLOGY

Students follow a five-step approach to carry out their project:

1. Problem Definition: Following a literature search, students define the problem in general terms and explain why it is of interest. They provide conceptual sketches as appropriate and determine any given information on the problem, including constraints. They also discuss any global / societal issues involved.

2. Project Objectives: Students determine the objectives of the project in technical terms for each of the areas they plan to analyze (ex. aerodynamics, flight mechanics, structures, etc.).

3. Multidisciplinary Analysis: Students map out the various sub-problems (i.e. aerodynamics, flight mechanics, etc.), make reasonable assumptions, and develop a model for each one of them using appropriate theory taught in each of the courses involved.

4. Results: Results in each area are presented in the form of graphs, tables, and drawings.

5. Discussion: Results are discussed in the context of each course as well as in a holistic context. For example, a solution that is aerodynamically acceptable may be structurally impossible. This would not satisfy the overall purpose of the project.

6. Evaluation and Reflection: Students evaluate their solutions and the assumptions they made in each of their models. Depending on the problem, they may also discuss whether the solutions they propose are socially and ethically acceptable.

EXAMPLE PROBLEMS

Example 1: In Spring 2005, a team of three students explored the formation flight of commercial aircraft. The problem required integration of Aerodynamics (AE162) and Flight Mechanics (AE165).

1. Problem Definition: Formation flight of aircraft has been studied since the beginning of the 20th century. Recent increases in fuel cost and environmental concerns related to air pollution make this problem relevant today because of the possible benefits of reduced fuel consumption and exhaust emissions. On the other hand, formation flight of transport aircraft may result in loss of flexibility in airline scheduling and raises safety concerns due to the close proximity of the aircraft flying in formation. Hence, the clearance required for safety reasons must be compared with the spacing required to achieve induced drag reduction.

2. Project Objectives: In aerodynamics the objectives were to (a) estimate the total drag reduction for a cluster of airplanes flying in formation and (b) determine the minimum number of aircraft that would result in significant drag reduction, and (c) determine the best lateral and longitudinal spacing. In flight mechanics the objectives were to estimate (a) the total fuel savings for a given route, and the (b) extended range (c) reduction in exhaust emissions, (d) cost benefits to the airlines, resulting from these fuel savings.

3. Multidisciplinary Analysis: In the aerodynamics course students used horseshoe vortices to model aircraft wings and their wakes. Their calculations started with the induced (vortex) drag of each airplane as well as the total drag of the formation. In the flight mechanics course students used the Breguet range and endurance equations as well as empirical data found in the literature to estimate fuel savings, extended range, and reductions in cost as well as in exhaust emissions.

4. Results and Discussion: In a moderately sized formation of 10 to 15 aircraft, the planes in the rear of the formation can expect an approximate reduction of 12% in total drag, with a resulting 15% increase in range or endurance.

5. Evaluation and Reflection: These results compared well to previously published data [11] hence the assumptions made in the modeling of the problem were reasonable. However, as expected, the optimum spacing required for significant savings was found to be rather small. As a result, formation flying may be possible only with a new generation of guidance and control systems, that will allow aircraft to broadcast their GPS coordinates to other aircraft in their vicinity [12].

Example 2: In Fall 2005, a team of four students optimized the geometry of a ramjet engine inlet. The problem required integration of Compressible Flow (AE164) and Aerospace Propulsion (AE167).

1. Problem Definition: Until the 1960's ramjets were used only in missiles. The development of the manned SR-71 Blackbird spyplane changed this trend, as it was designed to accelerate from takeoff to Mach 1.6 using a conventional turbojet engine and then switch over to a ramjet by opening various ducts and vents to allow the incoming air to bypass the compressor and the turbine. The performance of the ramjet engine is heavily dependent on the variable geometry inlet spike because it is used to position the internal shock wave and to control the boundary layer [13]. The next stage of ramjet development will likely be in the design of a Single-Stage-to-Orbit (SSTO) or Two-Stage-to-Orbit (TSTO) launch vehicle that incorporates a Rocket Based Combined Cycle (RBCC) engine. The vehicle will take off using turbojet engines, transition to ramjet mode in flight, switch to scramjet propulsion when the proper speed is reached, and then finish the acceleration to orbital velocity with a boost from a rocket [14]. The design of the inlet is critical in achieving good ramjet performance.

2. Project Objectives: In the compressible flow course the objectives were to (a) model the inlet flow for a Mach number of 2.5 at an altitude of 25,000 feet, (b) estimate the temperature at the entrance of the combustion chamber, and (c) calculate the stagnation pressure losses in the inlet. In the propulsion course the objective was to (a) optimize the inlet geometry for a fixed spike and a double wedge, and (b) calculate the efficiency of the inlet.

3. Multidisciplinary Analysis: In the compressible flow course students used shock and expansion wave theory to model the flow through the inlet and developed a spreadsheet to study this flow for various geometries. In the propulsion course students optimized the geometry to achieve the best possible efficiency.

4. Results and Discussion: Students calculated the number of shocks (including reflections), pressure losses, and overall inlet efficiency for various wedge angles and cowling radii of curvature, assuming single and double wedge configurations. For each configuration, they also calculated the temperature at the entrance of the combustion chamber. Their conclusion was that the double wedge configuration was best with an estimated efficiency of 0.92.

5. Evaluation and Reflection: Students benchmarked their spreadsheet using data from the SR-71 inlet. With the exception of the temperature at the entrance of the combustor, their results (number of shock reflections, pressure loss, inlet efficiency) compared very well with published data.

INTEGRATING MORE THAN TWO COURSES

In Spring 2006 students were encouraged to integrate in their projects as many courses as they could. The following proposal, submitted by a team of two students, is an excellent example of the level of integration that is possible in a single project:

Project Objective: *To design a flexible wing Unmanned Aerial Vehicle (UAV) for higher maneuverability and a larger optimum flight envelope than a vehicle with conventional wings.*

AE 162 – Aerodynamics: Wind tunnel testing of the flexible wing. *Experimental data will be collected from a series of wing models, each at a different wing configuration. A total of five configurations will be considered. The aerodynamic forces will be determined from wind tunnel tests using force measurements from a dynamometer and measurements of pressure distributions over each wing. The variables to be determined from these experiments are the coefficients of lift, drag, and moment about the wing spars. There will be two spars supporting this wing, one at the quarter chord and one at the half chord points. Each wing model will also be tested through a range of angles of attack to determine the angle for maximum lift-to-drag ratio. This information will be used to change the wing incidence and the mounting positions of the wing spars relative to the airframe in order to improve the efficiency of the vehicle.*

AE 169 – Computational Fluid Dynamics: Numerical solution for the flow over the wing with CFD++. *A numerical solution will be sought for each wing configuration. These values will be benchmarked with the experimental data determined from the wind tunnel testing. For the numerical solutions in the compressible flow range, linearized theory will be used to obtain the compressible aerodynamic coefficients from the measured incompressible coefficients.*

AE 114 – Aerospace Structures: *The initial structure will be designed using SolidWorks to meet the required operation and space requirements. Analysis of internal loads, stresses and deformation will be performed to investigate structural capability. A safety factor of 1.1 will be used since the vehicle is intended to be unmanned. The longevity of the vehicle will be determined based on selected materials and fatigue analysis.*

AE 165 – Flight Mechanics: *Using the measured data and the numerical solutions along with an assumed fuselage shape and weight, the following flight characteristics will be determined: (a) stall, takeoff, and landing speed, (b) maximum thrust required for takeoff, (c) propulsion characteristics like specific fuel consumption, and (d) the vehicle flight envelope.*

ME 120 – Experimental Methods: *Wind tunnel data (force and pressure) will be collected using a variety of sensors and LabView. An uncertainty analysis will determine the accuracy, precision, and validity of the measurements.*

ASSESSMENT

The rubric used to evaluate project reports is shown in Table II. Table III shows the number of projects, number of students who participated in projects each semester, the courses integrated, and statistics on project ratings. Students who receive "good" rating or higher, tend to interact more frequently with the instructors of each course, asking questions, checking answers, and seeking direction for their research. To encourage more frequent student-faculty interaction, bi-weekly progress reports were required for the first time in Spring 2006. As a result of this requirement, all projects received "excellent" or "good" ratings (last column in Table III).

BENEFITS

A problem-based, integrated engineering curriculum offers the following benefits:

- Students acquire open-ended and multidisciplinary problem-solving skills. These skills include the ability to see problems from a broader perspective.
- Capable, motivated undergraduates have an opportunity to engage in research work under the supervision of two or more faculty members as part of their coursework.
- This work is often publishable, usually in student journals and sometimes even in professional journals. Moreover, students can present their work in conferences.
- The approach described here is very flexible. Students do not have to register in a special, multi-unit course, as is the case with most integrated curricula. Moreover, they can choose any number of courses to integrate through their project, according to their comfort level with the material in each subject matter.
- Faculty members who supervise such projects become more aware of material taught in other courses and may see opportunities to collaborate in multidisciplinary research projects with their colleagues.

CONCLUSION AND FUTURE DIRECTION

The paper described a flexible, problem-based approach to integrating engineering courses. The student performance and the quality of the projects produced in the first three cycles (Table III) were encouraging and the feedback from the students who participated was very positive. The next steps in expanding the integration of our curriculum may include:

- Integration of additional non-aerospace engineering courses. For example, students who take Heat Transfer (ME114) may perform a heat transfer analysis in the combustion chamber or in the nozzle of a rocket engine (AE167).

- Integration of senior year electives with the senior design project (AE170A&B). This approach will increase the depth of analysis in the senior design projects and provide opportunities for students who take various elective courses to work on more practical and relevant applications of the material. For example, students who take AE169 may perform a CFD analysis of the wing of the airplane they design in AE170A&B.

TABLE II
RUBRIC USED TO EVALUATE PROJECT REPORTS

	Poor	Acceptable	Good	Excellent
1. Problem Definition	▪ Unclear. ▪ Does not describe the practical applications and importance of the problem. ▪ Does not provide any evidence or understanding of current literature. ▪ Is not technically relevant. ▪ Does not integrate principles from all courses involved. ▪ Does not address any contemporary societal issues.	▪ Clear. ▪ Describes the practical applications and importance of the problem. ▪ Refers to current literature (3+ references). ▪ Somewhat technically relevant. ▪ Somewhat interesting. ▪ Integrates principles from all courses involved. ▪ Addresses contemporary societal issues.	▪ Clear. ▪ Describes the practical applications and importance of the problem. ▪ Refers to and demonstrates understanding of current literature (3+ references). ▪ Technically relevant. ▪ Interesting. ▪ Integrates principles from all courses involved. ▪ Addresses contemporary global / societal issues.	▪ Very clear. ▪ Describes the practical applications and importance of the problem. ▪ Refers to and demonstrates understanding of current literature (5+ references). ▪ Technically relevant. ▪ Very interesting and new. ▪ Integrates principles from all courses involved. ▪ Addresses important contemporary global / societal issues.
2. Project Objectives	▪ No objectives. ▪ Unclear objectives ▪ Not written in technical terms ▪ Not addressing each and every area (aero, structures, flight mechanics, etc.) integrated in the project.	▪ Written in technical terms. ▪ Address each and every area (aero, structures, flight mechanics, etc.) to be integrated in the project.	▪ Clear. ▪ Written in technical terms. ▪ Address each and every area (aero, structures, flight mechanics, etc.) to be integrated in the project.	▪ Very clear. ▪ Written in concise, technical terms. ▪ Address each and every area (aero, structures, flight mechanics, etc.) to be integrated in the project.
3. Multidisciplinary Analysis	▪ No assumptions listed. ▪ Incorrect modeling. ▪ Superficial or incorrect analysis in one or more areas. ▪ No use of modern tools.	▪ Some assumptions listed. ▪ Correct modeling. ▪ Correct analysis in each area. ▪ Use of modern tools in some areas.	▪ Appropriate assumptions listed. ▪ Correct modeling. ▪ In-depth analysis in each area. ▪ Use of modern tools in some areas.	▪ All appropriate assumptions listed. ▪ Correct modeling. ▪ In-depth analysis in each area. ▪ Use of modern tools in all areas.
4. Results	▪ Poor quality graphs and tables. ▪ Numbers and trends do not make sense. ▪ Results do not agree with published data.	▪ Graphs and tables are prepared following standard guidelines. ▪ Some of the results make sense ▪ Some agree with published data.	▪ Good quality graphs and tables. ▪ Numbers and trends make sense. ▪ Results agree well with published data.	▪ Excellent quality graphs and tables in all areas. ▪ Numbers and trends make sense in all areas. ▪ Results agree very well with published data.
5. Discussion	No understanding of the results is evident in one or more subjects.	Some understanding of the results is evident in most subjects.	A good understanding of the results is evident in most subjects.	An excellent understanding of the results is evident in all subjects.
6. Evaluation and Reflection	▪ Superficial or no evaluation of the results. ▪ No reflection on the assumptions made to model the problem. ▪ No understanding of the impact of the solution in a practical, global / societal context is evident.	▪ Some evaluation of the results. ▪ Some comments on the assumptions made to model the problem. ▪ Some understanding of the impact of the solution in a practical, global / societal context.	▪ Good evaluation of the results. ▪ Reflection on the assumptions made to model the problem. ▪ Good understanding of the impact of the solution in a practical, global / societal context.	▪ Excellent evaluation of the results. ▪ Appropriate reflection on the assumptions made to model the problem. ▪ Excellent understanding of the impact of the solution in a practical, global / societal context.

TABLE III
PROJECT STATISTICS

	No. of projects	No. of students who participated in projects (total)	No. of students in each class (average)	Courses integrated into the projects	No. of projects with “excellent” rating	No. of projects with “good” rating	No. of “acceptable” projects
Spring 2005	5	15	26	AE162 AE165	2	1	2
Fall 2005	4	11	25	AE164 AE167	2	1	1
Spring 2006	4	12	26	AE114 AE162 AE165 AE169 ME120	2	2	0

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