AC 2010-2161: A CASE STUDY APPROACH TO TEACHING AIRCRAFT PERFORMANCE: REVERSE ENGINEERING THE SR-71 BLACKBIRD

Brian German, Georgia Tech

Brian German is an assistant professor in the Daniel Guggenheim School of Aerospace Engineering at the Georgia Institute of Technology. His research interests are in the areas of systems integration and optimization, aircraft conceptual design, and engineering education.

A Case Study Approach to Teaching Aircraft Performance: Reverse Engineering the SR-71 Blackbird

Abstract

This paper describes an approach and initial experience of incorporating case study assignments into an undergraduate course in aircraft performance. The concept is to pose a problem that involves reverse engineering a historical aircraft from performance data available in the public domain. The problem is framed as a case study in which students are encouraged to imagine themselves in a real-world role. Students are referred to a limited number of publications and performance data of questionable quality and are asked to assess the information and to answer a series of case questions. An initial implementation of the approach has been completed via the example of the SR-71 Blackbird reconnaissance aircraft. As a famous high-speed and visually stunning aircraft, the SR-71 is a compelling and well-known example to many aerospace students that serves to motivate interest in the assignment. Students are asked to imagine themselves in the role of a 1960s-era Soviet intelligence analyst tasked with determining the characteristics of the aircraft from observed performance and intercepted design data. In the paper, the value of the case approach in engineering is reviewed, the SR-71 case is described, and results and lessons-learned from the initial teaching trial are presented. The students' results are investigated statistically, and an assessment of the learning value of the approach is provided by the analysis of post-assignment student surveys. Conclusions are then drawn regarding the potential broader applicability of the case method for both aircraft performance and other courses in the aerospace engineering curriculum.

Introduction

Case studies are teaching methods based on historical scenarios that typify the practice of a profession. Cases have been used effectively in fields including medicine, law, and business management to provide real-world context to curriculum material and to foster a learn-by-doing approach to practical problem solving. The use of case studies in engineering education appears to be more limited than in these other professional fields.

Inspired by case-based approaches to engineering education, this paper describes an initial experience of incorporating a case study assignment into an undergraduate course in aircraft performance. The teaching trial was intended as a prototype experience to evaluate the effectiveness of a more holistic application of case studies in the aerospace engineering curriculum.

Performance courses are especially suitable for applications of the case method because historical aircraft can serve as powerful examples of attainable performance of different aircraft types. The performance course is also the point of entry for students in the aerospace design curriculum, insofar as performance methods enable both aircraft configuration sizing and the analysis of mission performance requirements. Because of this strong connection, the performance course offers a pedagogical opportunity to begin the process of teaching students the skills needed for effective aircraft design. Design requires a deep base of experience, and the case method offers promise as a way of building this experience through real-world example problems.

The focus of the case study approach to aircraft performance developed in this work is to pose a problem that involves reverse engineering a historical aircraft from performance data available in the public domain. The problem is framed as a scenario in which students are encouraged to imagine themselves in a real-world engineering role. Students are referred to a limited number of publications and performance data of questionable quality. They are then asked to assess the information and to produce first-order estimates of aircraft aerodynamic, propulsive, or weights characteristics based on reverse engineering the performance.

The initial implementation of the approach has been completed via the example of the SR-71 Blackbird reconnaissance aircraft. As a famous high-speed and visually stunning aircraft, the SR-71 is a compelling and well-known example to many aerospace students that serves to motivate interest in the assignment. Students are asked to imagine themselves in the role of a 1960s-era Soviet intelligence analyst tasked with determining the characteristics of the aircraft from observed performance and intercepted design data. The deliverable is a powerful 5-7 page "executive summary" replete with analysis results that is appropriate for briefing senior officials.

In the paper, the value of the case approach and experiential learning in engineering is reviewed, the SR-71 case is described, and results and lessons-learned from the initial teaching trial are presented. The students' results are investigated statistically, and an assessment of the learning value of the approach is provided by the analysis of post-assignment student surveys. Conclusions are then drawn regarding the potential broader applicability of the case method for both aircraft performance and other courses in the aerospace engineering curriculum.

Motivation for the Case Study Approach in Aerospace Education

The case method is a pedagogical approach that is commonly employed in the social sciences, medicine, and most commonly, business management. The technique is based on the study of particular incidents or series of events that have occurred in the practice of a profession. For instance, a medical case may focus on a presentation of a disorder or disease encountered by the instructing physician while treating a particular patient. The examination of a case is termed a *case study* or *case analysis*.

In a case study, students are typically presented with a series of facts, observations, and circumstances that describe the beginnings of a difficult or unknown situation that must be solved. For instance, in medicine, the case description may consist of the results of medical examinations, tests, and questions to the patient about symptoms. In many cases, this information is presented in the form of a written prose narrative with interspersed figures and tables. The narrative is in some ways similar to the beginnings of a movie plot that frames a depiction of a real-world scenario that can readily be imagined by the students. As the suspense reaches its apex, however, the case narrative stops abruptly, leaving the readers in a state of suspense. The students are left with a sense of the salient facts of the case and knowledge of how the scenario has unfolded.

Once this narrative has been told, a series of case questions are then presented. In some cases, the questions ask the students to determine a solution to the particular immediate problem set up in the case, whereas in others, the questions ask students to focus on broader systemic problems that may have contributed to the formation of the immediate problem. For instance, a business case may ask why a new product did not sell as expected, or it may ask why the company has not been able to introduce competitive products for the past several years.

The task of the students is then to examine these questions in the light of the information provided in the case. They must think creatively about the problem and speculate about causes and solutions. Cases are rarely "clear-cut," so students must build their opinions on the case by amassing as much substantiating evidence from the narrative, figures, and tables as possible. In many situations, particularly in business cases, some degree of numerical or statistical analysis is required to understand underlying trends in the data. In some cases, students are asked to work collaboratively in teams to mimic a team environment that would be involved in the real-world scenario. In others, the students are instructed to work alone. A thorough description of the case teaching method is provided by Boehrer.[1]

This case-based approach to learning is extremely powerful. It has been adopted almost unanimously by top MBA programs, and indeed, the technique was developed as a teaching tool primarily at the Harvard Business School during the 1950s.[2] Many of the skills developed through case analysis are difficult to gain through other educational methods. These skills include the following:

- Understanding when or if to apply particular analysis and/or numerical techniques to different facets of real-world problems, i.e. cases are "word problems" in the most general sense
- Multi-disciplinary understanding and connections, i.e. case solutions encourage students to think beyond the bounds of a particular disciplinary area or a particular course in order to amass the knowledge and techniques needed for a feasible solution
- Inductive logical reasoning, i.e. through a particular case, the students learn to anticipate generalities of entire classes of problems
- Creativity in the development of solutions, i.e. "thinking outside the box" is enabled because of the free-form nature of the problems
- Practicality in proposed solutions, i.e. reasoning in the real-world context encourages students to think about whether a proposed solution could actually be implemented from the standpoint not only, e.g. of technology/physics, but also of cost and schedule
- Experience, i.e. students "learn by doing" and develop practical skills more rapidly. In business or technical fields, students also gain an understanding of the order of magnitude of numbers.

As with most real-world scenarios, the "correct" answers to a case are not known. For instance, if a company collapsed because of problems in introducing a new product, it is not always clear that any *particular* change to the product or approach would have prevented failure of the business. Even if the case narrative refers to a circumstance whose historical outcome is known, it is not always clear that the students' solutions to the case would improve upon or degrade the situation that played out in the actual situation. In other circumstances, a particular correct answer may be known, but this data may not be available in the public domain, either because of company proprietary considerations (in management and engineering cases) or federal privacy regulations (in medical cases). For these reasons, the focus of case grading is typically to assess students not on the "correctness" of a particular solution, but rather on the elements described above, e.g. analytical techniques, logical reasoning, and creativity.

The unique skills taught by the case method make it an intriguing pedagogical approach to include in aerospace engineering instruction. With the well-known ongoing and impending erosion of the experience base within the aerospace workforce reported by the Commission on the Future of the U.S. Aerospace Industry,[3] case-based instruction offers the potential to produce new engineers with substantially greater experience in problem solving for real-world scenarios.

The value of the case approach in engineering education has been shown by Henderson[4] and has recently been articulated as a priority by the National Research Council (NRC) in the publication *Educating the Engineer of 2020: Adapting Engineering Education to the New Century*:

> Engineering educators should introduce interdisciplinary learning in the undergraduate curriculum and **explore the use of case studies of engineering successes and failures as a learning tool.**[5]

Instructional techniques similar to case studies that are employed frequently in aerospace engineering programs include the capstone design course and design-build-fly competitions. These design programs mimic cases in many ways, but there are several differences. First, students typically participate in only one or two such design/build activities throughout their education, whereas a case approach could form a holistic teaching and learning approach that could be integrated throughout the curriculum. Second, these design activities are often formulated for students to execute one design from start to finish during an academic term. Cases, on the other hand, can deal with a more limited scope of a larger problem and still provide effective real-world context and experiential learning opportunities.

The inclusion of inspiring historical case studies in aerospace engineering alongside other approaches is anticipated to broaden the spectrum of student learning styles engaged. This spectrum of styles has been described by Felder,[6, 7, 8, 9] and interspersing teaching methods tailored to each style in a balanced way is more likely to be successful in the aggregate than a siloed approach focused on a single method. The case study approach is anticipated to inspire and engage students who were motivated to pursue aerospace engineering because of their interest in historical aircraft or spacecraft, and it should also be effective for students whose learning is facilitated by immersion in believable real-world scenarios.

There is some precedent for a case-based approach to engineering instruction in the aerospace field. AIAA has prepared several cases that outline the development and/or production of certain aircraft such as the C-5,[10] Concorde,[11] and F-16,[12] but these cases are framed more as programmatic descriptions and not as problem-solving exercises suitable for students. Pedagogical case studies and other forms of Problem Based Learning (PBL) have also been advocated within the context of the MIT CDIO framework for aerospace education.[13, 14, 15]

This paper describes an initial attempt at a pedagogically-oriented case study in the area of aircraft performance based on the Lockheed SR-71. This prototype experience was intended to gauge the utility of the case method for broader application in the aerospace engineering curriculum.

The SR-71 Case Assignment: A Prototype Experience

The undergraduate aerospace vehicle performance course was selected as the venue for the initial case study trial. Vehicle performance is a three semester hour course taught during the third year of the aerospace curriculum. During the course, students are exposed to fundamental performance analysis methods for fixed wing aircraft, rotorcraft, and space vehicles. The course precedes the capstone vehicle design sequence and the majority of the students' technical writing exercises required in the curriculum.

The Lockheed SR-71 Blackbird, shown in Figure 1, was chosen as the topic of the initial case study because it is a well-known and recognizable aircraft with compelling performance that has frequently been the subject of popular books, television programs, and museum displays. Performance data for the airplane to form the basis of the case assignment are also available from a variety of sources. An additional motivation was that the SR-71 is featured as a design vignette in the course textbook.[16]

The SR-71 case was formulated to achieve the following goals:

- Reconnect students to their inspiration and passion for the field of aerospace engineering by working with the example of a legendary high performance historical aircraft.
- Require the use of historical data from disparate sources of questionable quality to illustrate the empirical nature of some elements of engineering, especially in conceptual design and aircraft performance.
- Encourage critical thinking to assess the quality of empirical data and to adjudicate the applicability and uncertainty of each data source for use in engineering analyses.
- Develop skills in "reverse engineering" in aircraft performance.
- Exercise and reinforce the analytical performance methods developed during lectures.

Figure 1: SR-71 in Flight (Source Cited in Figure)

The assignment introduced the airplane and posed a role-playing scenario for the students that provided context for the reverse engineering activity:

> The SR-71 Blackbird is a high-altitude high-Mach reconnaissance vehicle built by Lockheed's Skunk Works organization in the 1960s. The SR-71 was operated by the CIA in ingress photoreconnaissance flights over the Soviet Union and other Eastern Bloc states for over two decades. The production aircraft was the outcome of a long series of design studies that began in 1956 after the U-2 was fielded. The SR-71 design team was led by Clarence L. "Kelly" Johnson, one of the most celebrated and colorful aeronautical engineers of all times. Kelly was creative, demanding, and efficient in developing innovative new aircraft designs such as the P-80, U-2, and SR-71 on schedule and on budget.
>
> Your task in this case study is to understand the SR-71 development program and to reverse engineer its aerodynamics at cruise conditions. Much of the real-world data for this aircraft remains classified or Lockheed proprietary, so your task will involve assembling disjointed pieces of information from various public domain sources. You will need to assess the credibility/applicability of the data for the particular flight conditions being considered and to use the data in conjunction with your knowledge of aerodynamic and flight performance to develop first-order credible estimates. It is your task to amass and assemble the data with your expertise without specific step-by-step instructions; this is the role of engineers in the real world.

This reverse engineering task puts you in a role analogous to a Soviet intelligence expert from the 1960s trying to understand this incredible new threat to your national security. Your deliverable is to provide answers to the questions on the following page in the form of an information-dense 5-7 page "executive summary" that can be reported to senior officials. Your KGB superior will not tolerate long-winded rambling discussions; keep your wording concise, elegant, and powerful, and make a compelling case using data and equations.

The specific tasks based on this case scenario were grouped into two areas: (1) development program and the resulting design, and (2) aerodynamics at cruise. The tasks in the first area were framed largely as a "book report" on the SR-71 design and technical challenges. These tasks were formulated to ensure that students obtain and read background materials about the airplane to frame the problem. The second area provided a series of steps that built ultimately to the reverse engineering of the cruise drag polar as the primary task. Because the case was assigned in the first month of the semester-long performance course, detailed aero-performance analyses beyond steady cruise point performance were not considered. The case analysis tasks were as follows:

1. <u>Development Program and the Resulting Design:</u>
    a. There were several significant technical challenges that had to be overcome during the SR-71 development. These challenges were related to the Mach/altitude operating envelope and the mission of the aircraft. Name and briefly describe at least three of these challenges and describe how they were solved by Kelly Johnson and his engineering team. Some of these challenges were discovered during the evolution of the conceptual studies that preceded the SR-71 design, and others were identified after the aircraft was initially fielded. Your descriptions should be concise; target approximately 1-2 paragraphs for each challenge.
    b. Provide a brief description (1-2 paragraphs) of the resulting SR-71 configuration. Create a table that summarizes configuration parameters of interest to a performance engineer, e.g. wing parameters, weights, sea-level static maximum thrust, etc. Make sure that you include all design parameters that you will need for your calculations in Task 2 below.

2. <u>Aerodynamics at Cruise:</u>
    a. Describe a typical high-speed cruise segment for a reconnaissance mission. Create a table summarizing the cruise Mach number, altitude, initial and final weights (most airplanes burn fuel when they fly), range of the cruise segment, and other mission values that are important. You will need to read some of the flight manual information to estimate these weights, ranges, etc. This information will be used to define the reference condition(s) for your aerodynamic analysis.
    b. Lift at initial cruise weight
        i. Estimate the lift at the beginning of a typical cruise segment
        ii. Calculate the corresponding lift coefficient

iii. Estimate the angle of attack at which the aircraft operates to produce this lift

c. Drag at initial cruise weight

i. Locate a representative set of cruise drag breakdown data in the literature sources provided. Presume that this drag occurs at the initial cruise weight. Estimate the total drag based on this data. Describe/justify the presumptions that you need to make to attain this estimate.

ii. Calculate the corresponding drag coefficient.

iii. Calculate the L/D at this cruise condition. Is this a "good" value of L/D?

d. Drag polar. Estimate a parabolic drag polar for the SR-71 at your chosen cruise condition. Specifically, given a parabolic polar of the form, $C_D = C_{D,\min\,drag} + k\left(C_L - C_{L,\min\,drag}\right)^2$, estimate k, $C_{D,min\,drag}$ and $C_{L,min\,drag}$. Three conditions or points are needed to define this parabola. One point is determined by your answers to 2.b.ii and 2.c.ii above. You need to find two other points and/or conditions. The data that you found for 2.c.i may arguably provide at least one additional point. To find information needed for the additional condition(s), you have several options: (1) correct some available C_D and/or C_L data found at other Mach numbers and angles of attack, (2) find data related to the *maximum* L/D at this cruise condition (not necessarily the L/D found in 2.c.iii), (3) back-calculate additional points from performance information provided in the data sources above, or (4) make and justify some simplifying presumptions. Describe the method that you choose as well as your reasoning. Indicate the amount of trust that you have in your answers based on the validity of quadratic model and on the quality of the available data. What additional data would help to improve your estimate?

e. Lift and drag at final cruise weight. Based on your drag polar calculated above, repeat your analyses from 2.b and 2.c for the final cruise weight. Discuss the differences from the initial cruise weight. Is L/D higher or lower? Why?

f. Engine-out descent. Presume that the engines flame out at the initial weight cruise condition. Calculate the instantaneous values of the following performance metrics immediately after flameout:

i. Rate of descent

ii. Angle of descent

Limited sources of data were recommended to the students as a starting point to minimize the required literature search effort. Nonetheless, the students were encouraged to locate additional sources of data. The assignment specified that all data was to be referenced to its source, with full citations provided in a references section at the end of the case report. The students were also asked to gauge the validity and applicability of all data from these and other disparate sources for credible engineering analysis of the case study problems. The sources recommended were as follows:

- Conference and journal papers
    - Merlin, P.W., "Design and Development of the Blackbird: Challenges and Lessons Learned," *47th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exposition*, 5 - 8 January 2009, Orlando, Florida.
    - Campbell, D. H., "F-12 Series Aircraft Propulsion System Performance and Development," *Journal of Aircraft*, **11**(11), 1974.
- Online sources
    - SR-71 Wikipedia article (http://en.wikipedia.org/wiki/SR-71_Blackbird)
    - SR-71 flight manual (http://www.sr-71.org/blackbird/manual/)

The case study was specified as an individual student assignment with three weeks to complete. The analytical tasks portions were commensurate in difficulty with a homework assignment that would normally be assigned for a single week of effort. The challenge of the assignment was associated primarily with the difficulty of locating and reading data sources and assembling and assessing the information for carrying out the analyses. The final deliverable was a powerful five to seven page report that introduced the problem and answered the required questions. Students were given wide latitude in formulating the report format and style, with the only guidance being that the result should be "professional" and in the spirit of the context of the case assignment.

Assignment Results

After the students submitted their reports, numerical results were tabulated to allow for statistical analysis, and general trends in the students' writing, analysis approaches, and answers were documented. The following general observations were made:

- Reports were generally well written and commensurate with the students' progress in the curriculum. The reports could be categorized stylistically into three groups:
    - Creative in-depth reports in first-person prose in which students played the role of a KGB analyst. These students seemed to enjoy and be inspired by this role-playing context of the problem.
    - Crisp and ample professional reports in third-person without specific mention of the KGB analyst role.
    - Documents that enumerated and answered the task questions tersely without providing adequate details and explorations in the written report.
- Most students (approximately 90%) did well on first task area, indicating that they had read and understood the sources describing the SR-71 configuration, mission, and development program. These students correctly identified technical challenges in the program including stealth, thermal management, and manufacturing issues with new structural materials.
- For task 2.a, most students (approximately 90%) tabulated reasonable design mission parameters, based primarily on information in the SR-71 flight manual. A specific mission was not indicated in the assignment, so substantial variability in the students' values was noted based on varying interpretations of the flight manual. This variability in the mission specification was a source of substantive variability in the subsequent aerodynamics analysis results.

- Approximately 80% of the students did well in the analytical lift and drag calculation tasks 2.b and 2.c. Based on the information involving the aircraft configuration and mission, these point calculations were straightforward. In task 2.c.iii, most students identified reasonable L/D values in the range of 5-9 for this aircraft type.
- Task 2.d was found to be extremely challenging, with only approximately 20% of the students producing reasonable drag polars. Observations included the following:
    - Approximately 20% of the students did not complete task 2.d and/or did not indicate all of the drag polar parameters in their assignment reports
    - Some students demonstrated lack of understanding of how to calculate the parameters of a three-parameter quadratic drag polar based on three C_L and C_D data points
    - Some performed drag polar calculations based on widely separated Mach number and altitude conditions based on disparate data obtained in the flight manual
    - Even after answering 2.c.iii correctly by indicating a reasonable magnitude of cruise lift-to-drag ratio for the SR-71, many students (approximately 60%) calculated drag polars whose parameters implied $L/D >> 10$. These students likely did not check the lift-to-drag ratios produced by their drag polar parameters.
    - A small number of students calculated polars with negative drag
    - Of the 20% of students who calculated reasonable drag polars by tabulating multiple cruise C_L and C_D data points, the primary source of variability in their answers was the variability in their choice of the cruise Mach number condition from the flight manual for the calculations.
- Tasks 2.e and 2.f were performed correctly by most students who completed the drag polars; however, results depended on the correctness of the underlying polars calculated in 2.d.
- Most students commented only briefly about the validity/applicability of different data sources, but some noted that the values obtained from the Wikipedia entries may be less trustworthy than data from the other published sources.

A statistical analysis of the students' drag polars was conducted to determine the class' overall performance and to compare this performance to values of the SR-71 drag polar found elsewhere in the literature. Because of the variability in the students' parameter values, the following filters were applied to remove both technically nonsensical solutions and statistical outliers prior to the analysis:

- Technically nonsensical or improbable (approximately 60% of the results)
    - $C_D < 0$
    - $L/D > 10$
    - $L/D < 3$
- Statistical outliers (approximately 5% of the results) identified based on Chauvenet's criterion for departure from a normal distribution

The purpose of this filtering approach is to produce a statistical analysis that indicates the variability associated with "reasonable assumptions" in reverse engineering activities based on disparate data. Although the resulting statistical analysis was not complete in time to present to the students, the intent is to use this type of analysis in future case studies to demonstrate the difficulty of empirical approaches in reverse engineering and other performance and design contexts.

The results of the statistical analysis are presented in Figure 2 below in comparison to the polar estimated by Mixon, *et al.* based on calculations for the SR-71 geometry using the Air Force digital DATCOM computer program.[17] As indicated in the figure, the mean value of drag coefficient calculated by the students was approximately 25% lower than the DATCOM value. The variability in the students' results, even after the removal of technical and statistical outliers is considerable, with a standard deviation of approximately 50% of the mean drag value. This variability difference is substantive, demonstrating the variability from several sources including the underlying data presented in the references, the students' interpretation of relevant cruise conditions, and the various assumptions made in the drag polar calculations. The DATCOM results lie within one standard deviation of the class' mean value, however.

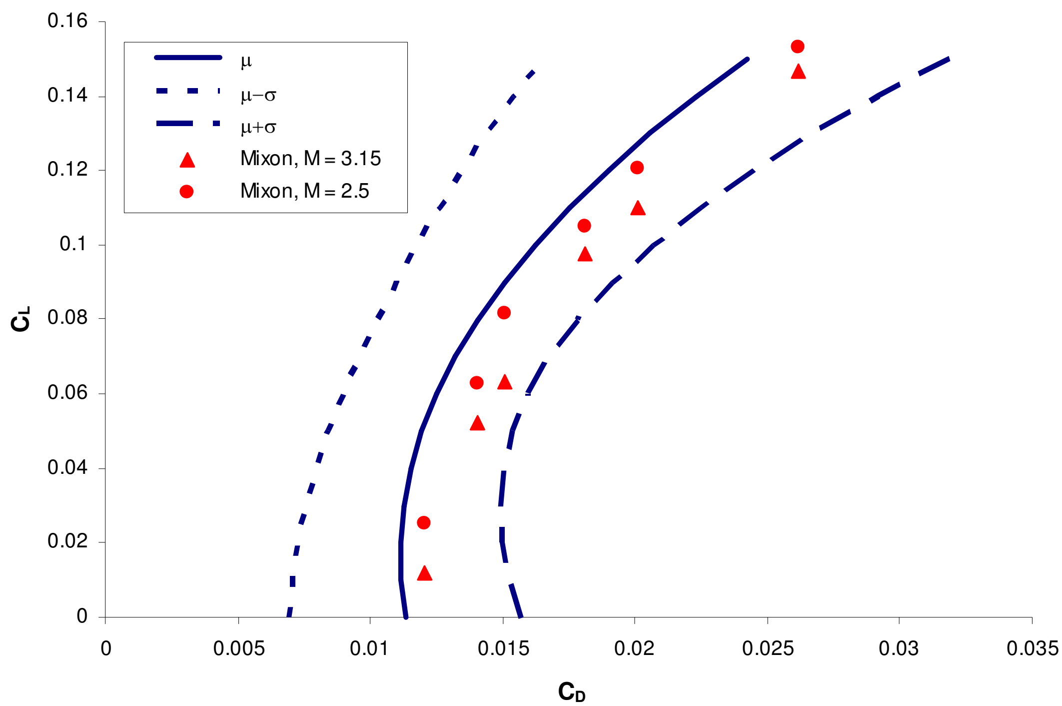

Figure 2: Statistical Drag Polar Results

After the assignments were returned, the students were surveyed to indicate their impressions of the case assignment and its learning value. The survey was administered simply by providing paper and asking students to write a short few comments indicating their impressions. The responses were largely consistent and can be summarized as follows:

- The assignment was found to be enjoyable and inspiring, and the students learned many details about the SR-71 that they had not previously known. Several students indicated that the project reminded them of the reason that they had decided to become aerospace

engineers, as compared to the many esoteric and abstract assignments in their coursework throughout the degree program.
- It was difficult for many students to determine the appropriate data to use in calculating the drag polar based on the information in the recommended sources.
- Many indicated that the assignment clarified what a drag polar actually represents and how it is determined; others indicated that the assignment made it clear that they did not understand drag polars.
- Many students commented on the written report, noting that it was one of their first experiences of writing a professional technical document. These students indicated that they were unsure how to specify section headings, how to cite references of engineering documents, and of the writing style to use.
- The assignment took many hours to complete because of the need to read through many sources, and difficulty and length were incommensurate with its fraction of the course grade (7.5%).
- Many would have preferred the assignment to be a group project as opposed to an individual project.

Conclusions and Lessons Learned

This initial attempt at a historical case study in aircraft performance was reasonably successful. Students generally enjoyed the approach, sensed its learning value, and felt re-connected to their "dreams" that inspired their pursuit of an aerospace education. The open-ended and exploratory nature of the problem of determining the drag polar indicated a lack of fundamental understanding by some students that motivated additional lecture time to clarify the missed points. This lack of understanding would be more difficult to gauge in a homework or exam problem because of the necessity of specifying the precise information needed to solve the problem in these assessments.

Although generally successful, much was learned that can guide future case assignment formulations. A primary lesson is to bound the open-endedness of the problem statement carefully in order to limit loopholes in student interpretations and responses. Although a key objective of the case approach is to provide an open-ended exercise, the problem statement must be reviewed critically in order to "design in" the types of variability that are to be expected and encouraged. Indeed, the variability in the students' answers, as exemplified by statistical analyses such as in Figure 2, is a key aspect of the approach that can be used for additional post-assignment lessons on empiricism in reverse engineering. However, as indicated in Figure 2, the variability in results was quite large due to widely disparate data assumptions by the students. This variability is part of the lesson, but the instructor should ask carefully what specifically is to be measured and taught based on the individual and statistical results.

The case study approach appears to be a useful method for teaching and learning in aircraft performance and likely in other courses in the aerospace curriculum. Promising areas for case assignments include additional reverse engineering exercises in aircraft performance, controls, aerodynamics, structures, propulsion, and design throughout the curriculum. Case assignments offer considerable learning value, and this learning experience is greatly amplified by thoughtful post-assignment discussions and analyses of the aggregate class results and of particular solution approaches and common misunderstandings.

From the standpoint of course preparation, detailed cases may demand more of the instructor's time, insofar as efforts must be made to acquire historical data, write an inspiring case narrative, and test the problem statement before the assignment. It is the opinion of the author, however, that this additional time is well-spent.

Bibliography

1. Boehrer, J., Teaching with Cases: Learning to Question, *New Directions for Teaching and Learning*, Vol. 42, 1990, pp. 41–57.
2. Armisted, C., How Useful Are Case Studies? *Training and Development Journal*, Vol. 38, No. 2, 1984, pp. 75–77.
3. Final Report of the Commission on the Future of the United States Aerospace Industry, Tech. rep., 2002.
4. Henderson, J., Bellman, L., and Furman, B., A case for teaching engineering with cases, *Engineering Education*, 1983, pp. 1.
5. Committee on Engineering Education, Educating the Engineer of 2020: Adapting Engineering Education to the New Century, Tech. rep., National Academy of Engineering, 2005.
6. Felder, R. M. and Silverman, L. K., Learning and teaching styles in engineering education, *Journal of Engineering Education*, Vol. 78, No. 7, 1988, pp. 674–681.
7. Felder, R. M., Felder, G. N., and Dietz, E. J., The effects of personality type on engineering student performance and attitudes, *Journal of Engineering Education*, Vol. 91, No. 1, 2002, pp. 3–17.
8. Felder, R. M. and Brent, R., Understanding student differences, *Journal of Engineering Education*, Vol. 94, No. 1, 2005, pp. 57–72.
9. Felder, R. M. and Spurlin, J., Applications, reliabilty and validity of the index of learning styles, *International Journal of Engineering Education*, Vol. 21, No. 1, 2005, pp. 103–112.
10. Garrard, W. C., *The Lockheed C-5 Case Study in Aircraft Design*, AIAA Professional Study Series, AIAA, 1978.
11. Rech, J. and Leyman, C., *A Case Study by Aerospatiale and British Aerospace on the Concorde*, Library of Flight Series, AIAA, 1994.
12. Droste, C. S. and Walker, J. E., *The General Dynamics Case Study on the F-16 Fly-by-Wire Flight Control System*, Library of Flight Series, AIAA, 1998.
13. Crawley, E. F., Brodeur, D. R., and Soderholm, D. H., The Education of Future Aeronautical Engineers: Conceiving, Designing, Implementing and Operating, *Journal of Science Education and Technology*, Vol. 17, 2008, pp. 138–151.
14. Berggren, K.-F., Brodeur, D., Crawley, E. F., Ingemarsson, I., Litant, W. T., Malmqvist, J., and Östlund, S., CDIO: An international initiative for reforming engineering education, *World Transactions on Engineering and Technology Education*, Vol. 2, 2003, pp. 49–52.
15. Brodeur, D. R., Young, P. W., and Blair, K. B., Problem-Based Learning in Aerospace Engineering Education, *Proceedings of the 2002 American Society for Engineering Education Annual Conference & Exposition*, 2002.
16. Anderson, Jr., J. D., *Aircraft Performance and Design*, WCB/McGraw–Hill, 1999.
17. Mixon, B. D. and Chudoba, B., The Lockheed SR-71 Blackbird –-A Senior Capstone Re-Engineering Experience, *45th AIAA Aerospace Sciences Meeting and Exhibit, 8 - 11 January 2007, Reno, Nevada*, 2007.