Undergraduate Educational Research Activities in Aeronautical Engineering at the United States Air Force Academy

[1]D.N. Barlow. [2]T. E. McLaughlin, [3]C. F. Wisniewski
US Air Force Academy, USAF Academy, CO, USA, Neal.Barlow @usafa.edu[1];
US Air Force Academy, USAF Academy, CO, USA, Tom.Mclaughlin @usafa.edu[2];
US Air Force Academy, USAF Academy, CO, USA, Charles.Wisniewski@usafa.edu[3]

Abstract

During the past decade, the Aeronautical Engineering Department has purposefully transformed its curriculum and facilities to require both experimental and computational research as an integral part of its undergraduate educational program. Recognizing that experiment and computational knowledge and skills are critical and complementary to an undergraduate education, the curriculum has evolved to include both traditional and computational fluids course work and laboratory experiences. In addition, each student (cadet) is required to participate in a real-world research project in addition to the traditional year-long design experience. The traditional laboratory experience is accompanied by a requirement to conduct either an experimental or computational project that responds to a "real" customer's needs. USAFA is fortunate to have an outstanding experimental and computational infrastructure to support its undergraduate educational research activities.

1. Introduction

The Department of Aeronautics (DFAN), in existence since the organization of the United States Air Force Academy (USAFA) in 1955, has offered an accredited Aeronautical Engineering degree since 1967. DFAN has remained dedicated first and foremost to USAFA's unique and primary mission statement: *To educate, train, and inspire men and women to become officers of character, motivated to lead the United States Air Force in service to our nation*.[1] In the course of fulfilling this mission, cadets and faculty serving in DFAN have consistently achieved exemplary results in their military service, academic scholarship, and research during and after their USAFA attendance.

"Capable of flying at tremendous speeds (200mph) and executing astonishingly agile maneuvers, the Peregrine Falcon is a true ruler of the air, fully worthy of its fame as a raptor of unequaled predator abilities."[2]

A better mascot couldn't have been chosen for the men and women attending and serving at the United States Air Force Academy. With a sharp vision for integrity, service, and excellence, USAFA faculty and graduates have produced high achievements in all facets of U.S. Air Force operations and its research and development complex. Cadets (officer candidates) are challenged and stretched in their knowledge and intellect with an ABET accredited curriculum, an intense leadership laboratory environment, a comprehensive peer-driven character development program, and strenuous physical training.[3] Cadets are exposed to all facets of a world-class military air and space force. Many taste the freedom and discipline of flight in various training programs for the first time during their cadet career. Graduates leave USAFA with a Bachelors of Science degree and a commission as a Second Lieutenant. They join a "long blue line" of officers dedicated to leading airmen. They continue their education and service as weapons system operators, technical experts, specialists or in graduate student. As past graduates have reached the upper levels of leadership in USAF military service or civilian workforce, they've demonstrated the value of the unique USAFA educational experience.

While, a premium is placed on the development of officers via a well-integrated military training program including leadership development, physical fitness, athletic competition, and flight training, at the heart of a cadet's development is a robust core curriculum consisting of 102 academic hours divided between humanities (25 hours), social sciences (27 hours), basic sciences (27 hours), engineering (18 hours), and physical education (5 hours). The foundation of the experience is found in the values of the institution, expressed daily by a faculty of over 700 dedicated professors and staff, composed of civilian professors and military officers, supported by an exceptional enlisted, civil service and contract staff. The men and women of the USAFA faculty serve as role models and mentors for the cadets, sharing the warfighter spirit as well as their technical and leadership expertise. In addition to the required core, the Academy offers 32 academic majors as well as a foreign language minor. Thanks to the mission of the USAF, aeronautics and related fields contribute heavily to the Academy curriculum. The Aeronautical Engineering Department has 25 full time faculty members supported by approximately 30 laboratory and administrative staff members, including almost 20 researchers supported by a variety of research and grant funding. The major requires an additional 45 semester hours of engineering courses past the core curriculum, totalling 147 semester hours required for graduation.[1]

During the past decade, the Aeronautical Engineering Department has purposefully transformed its curriculum and facilities to require both experimental and computational research as an integral part of its undergraduate educational program. Recognizing that experiment and computational knowledge and skills are critical and complementary to an undergraduate education, the curriculum has evolved to include both traditional and computational fluids course work and laboratory experiences. In addition, each student (cadet) is required to participate in a real-world research project in addition to the traditional year-long design experience. The traditional laboratory experience is accompanied by a requirement to conduct either an experimental or computational project that responds to a "real" customer's needs. Customers are typically United States Department of Defense (DoD) research and development or acquisition offices. Other customers include DoD contractors and NASA entities. Students also have the opportunity for follow on summer research activities at DoD and contractor facilities as well as senior level independent study research opportunities which meet elective requirements and the opportunity to compete in the American Institute of Aeronautics and Astronautics' Regional Paper Competition. Cadets are provided with unprecedented opportunities for 'hands-on' experiences and for making contributions to 'real world' programs. Including the Class of 2011, DFAN has produced over 2,000 aeronautics engineers for service in the USAF.

Since 1955, over 300 faculty members have served within DFAN, supervised by 14 Department Heads. Historically, a majority of the faculty members have been active-duty military members, serving several years at the Academy before moving on to operational military assignments, advanced educational opportunities, or civilian life. With a Master of Science or Doctoral degree in Engineering, these military faculty members range in academic rank from instructors to full professors. Above and beyond the technical knowledge shared in the classroom, they serve as critical military role models for cadets. Their "war stories", involving character, integrity, and leadership issues as well as technical "been there, done that" wisdom, help the cadets internalize the Air Force's core values: *Integrity First, Service Before Self,* and *Excellence in All We Do*.

DFAN's civilian faculty members, either permanent or visiting, provide the backbone of continuity to the department's technical expertise and curriculum organization. With Doctoral degrees in Engineering and a wide range of prior military, academic, and industrial experiences, these professors help their cadets develop an understanding of their responsibility to their customers and the discipline, knowledge and skills required of professional engineers. Currently a third of DFAN's 25 faculty members are civilian. National and international current events, including USAFA and USAF policies, plans, and activities world-wide, are discussed regularly in the classroom alongside the aeronautics curriculum, keeping the institution's goal always front and center.

Beyond the classroom, the annual contributions of the DFAN faculty to the overall mission of the Academy via extracurricular activities are outstanding. In a typical year, the DFAN faculty and staff led over 60 cadet research and development projects in aeronautics and related fields, authored or co-authored over 30 professional papers and presentations, spent well over 100 hours in local schools or hosting student visits to the Academy, providing aerospace education to the local community, and served in over 20 different after-hours military leadership/mentorship positions with the cadet wing, providing academic counseling, ethics training, or supervision of the cadet-to-cadet training program.

2. Facilities

A critical component of the aeronautics major's education -- hands-on research and development -- occurs in the DFAN Aeronautics Laboratory. To implement the curriculum requires an extensive suite of facilities. USAFA is fortunate to have had a substantial investment in experimental infrastructure since its inception, and a series of upgrades over the years to keep them relevant. The Laboratory is a 7,500 m^3 facility housing nine major wind tunnels capable of various test velocities from low speeds to Mach 4.5, a water tunnel, three jet engine test cells including operational J-69 and F-109 cycles, a rocket/internal combustion engine test cell, two Genesis 3000 flight simulators, and a variety of smaller experimental equipment. Each major facility has a technician dedicated to its operation, maintenance and upgrade. This ensures they do not fall into disrepair, and establishes continuity in their operational capability.

The most versatile and well-employed facility is the Subsonic Wind Tunnel (Fig 1). The SWT, with a 0.91 x 0.91 x 3 m test section, operates at Mach numbers from 0.05 to 0.6 (clean tunnel). As this covers the range where most flight takes place, it is well-used. Fully a third of all research performed here is based in this facility. A well-developed internal force balance measurement capability allows six force components to be measured simultaneously, facilitating lift, drag, axial force, and pitch/roll/yaw moments to be determined. The tunnel will be upgraded in late Fall 2011 with an external force balance, capable of larger measurement ranges and state-of-the-art accuracy.

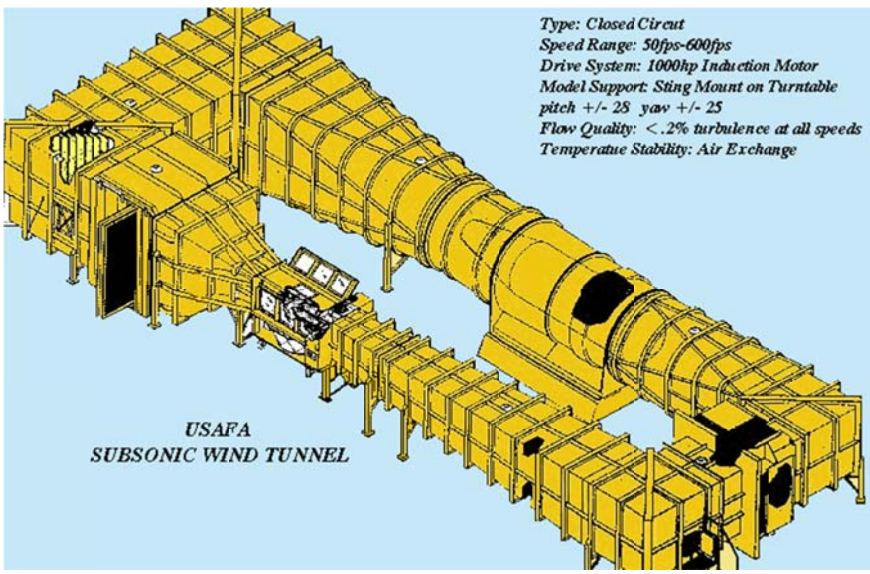

Figure 1 Subsonic Wind Tunnel Schematic

The Trisonic Wind Tunnel (TWT), Fig 2, complements the SWT with a high subsonic, transonic and supersonic capability. With a 0.3 x 0.3 m test section, it is a blowdown facility. Six tanks with 150 m^3 of storage can be pumped to over 3.5 MPa, resulting in test run time of up to three minutes, depending on Mach number. The tunnel has a continuous subsonic capability as low as M = 0.4 through transonic, with a variable porosity cart. Fixed nozzle blocks allow operation at Mach numbers of 1.39, 1.68, 2.02. 2.45, 3.48 and 4.38. A pressure control system allows the system to work at Reynolds numbers between 1 and 13×10^6 per meter.

Dual low speed wind tunnels as in Fig 3, also with test sections of 0.91 x 0.91 m cross section, complement the SWT. They operate at up to 30 m/s, and their simple, open-return design eases operation, allowing students to run the facility unsupervised. Like the SWT and TWT, they also have a well-developed force and moment measurement capability.

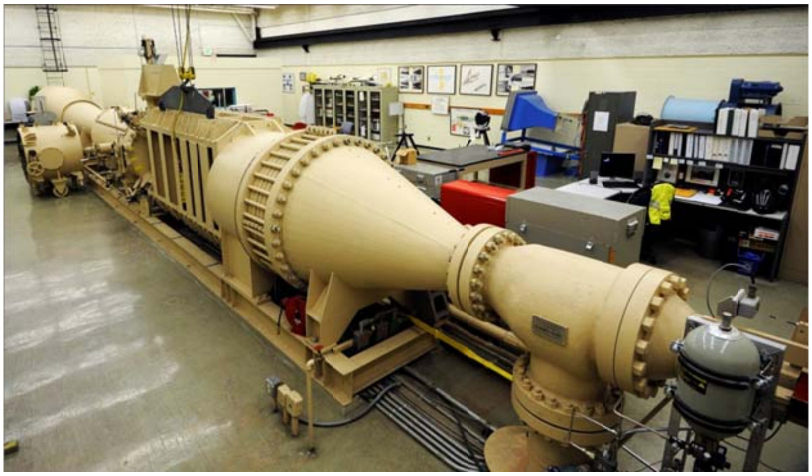

Figure 2 Trisonic Wind Tunnel

Figure 3. Low Speed Wind Tunnels

A water tunnel (Fig 4) provides a flow visualization capability to further illustrate findings from the other facilities. With a 38 x 51 cm test section, the water tunnel is primarily used with dye visualization to mark and track flow particle behavior. A particle image velocimetry system and laser Doppler velocimeter provide highly accurate and dense velocity information.

In addition to the wind tunnels, four hardened engine test cells provide for testing of gas turbine, internal combustion and rocket engines. Water brake and eddy current dynamometers are the main diagnostic tool for internal combustion performance, and heavily instrumented J-69 (Figure 5) and F-109 turbofan engine provide excellent platforms for diagnosing current research areas of interest, including engine swirl and stall.

In support of the computational education and research mission, the Department manages a SGI Altix ICE 8400 parallel processing computer system with 144 core processors, 2GB RAM per core and 6TB common RAID storage. This local capability is in addition to access to the large national HPC sites through the Defense Research Network. The Department has active computational research programs in virtual flight testing and system identification, aero servo optics and closed loop flow control and is the principle investigator of a 7M cpu hour U.S Department of Defense High Performance Computing challenge grant.

Figure 4. Water Tunnel

3. Experimental Education

The department's experimental efforts have evolved over an extended period. Twenty years ago, the extensive facilities were under-utilized and little productive research was performed. The requisite experimental methods class was then geared toward an understanding of all available means of measuring pressure, force, temperature and velocity. A smaller portion of the syllabus was devoted to an experimental effort under a faculty "sponsor", but these investigations were cursory and rarely focused on discovery of new knowledge. As, initially, a few goal-oriented, sponsored research efforts were undertaken for outside customers, it quickly became clear that the higher achieving students assigned these projects took away a great deal from the experience. Their depth of knowledge and appreciation of the discovery process seemed to be bearing great fruit for them, both in their graduate studies and their subsequent careers.

It was clear that students responded well to the challenges of a funded research project, where a sponsoring organization was very interested in, and were willing to pay for, the results of the students' investigation. The quality and volume of students' performance far outstripped that of those with "make work" experimental efforts. It became clear that the knowledge that their work was of importance to entities outside the academic environment produced an entirely different motivation. It was also clear that the students responded and benefited tremendously from the consistent and high level of interaction with their faculty sponsor. Not only did the faculty member provide mentorship through the experimental process, they modeled the behavior of the professional engineer in the solution of problems; students understood from example what the professional did when the experiment didn't work, the data were incorrect, or the outcome wasn't expected.

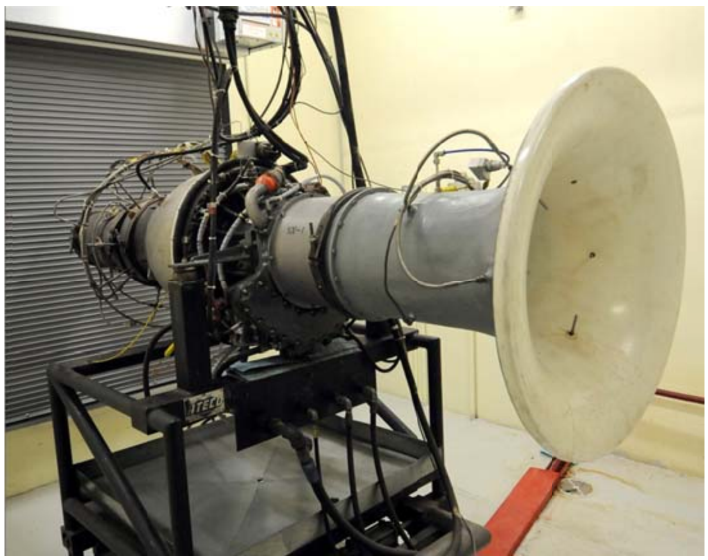

Figure 5. J-69 Turbojet Engine

Two substantial changes were then made to the experimental curriculum. First, a leadership commitment was made to extending to all students the "best practice" of participating in a real, timely and sponsored research effort. Commitment to attracting outside funding resulted in a trickle, then a stream and a river of outside sponsorship, over time. That sponsorship meant that additional full time staff could be hired to complement the strained faculty time available to support projects. At this point, teams of two cadets (never more than three) are paired with a faculty "team leader" in the solution of a current basic or applied, sponsored research program. This is now universal; all students majoring in aeronautical engineering, regardless of skill or grade history, participate in funded experimental investigations. To our knowledge, this is the only program in the world where this occurs at the undergraduate level.

A second, riskier change provided surprising results. Faculty team leaders regularly complained that there was insufficient time in the semester to complete the project. With half the semester taken up with theory and lecture, it became more and more difficult to complete everyone's project, especially since there was a need for more rigorous experimentation to meet sponsor needs. To provide the additional time, the classroom effort was cut in half, to only 10 lessons. This provided just enough time to introduce measurement systems and strain gauge-based transducers; discuss signal conditioning and data recording; and bring in statistical concepts and data uncertainty. Two laboratories to experiment with a cantilever beam force measurement and a hot film anemometer rounded out the effort before students began to concentrate on their projects. While it was feared that the elimination of more traditional surveys of all measurement techniques would weaken their experimental base, just the opposite happened. With the additional project time, students were able to delve more deeply into the measurement technology used in their particular experiment. They became experts in that methodology through repetitive use. Subsequently, with the knowledge that they could learn all that was needed about a particular transducer, they were much more keen and able to learn about different transducers on their own, without introduction in the classroom. In short, the time previously spent on comprehensive treatment of measurement technology wasn't missed.

A current list of projects indicates the eclectic nature of the research undertaken in support of undergraduate education (Table 1). Clearly, given the breadth of efforts, there can be little commonality of experience from one team to another. That appears to be of little consequence, as there are rarely complaints about differences in experience, either from the students or the organizations gaining their services after graduation.

Once students have gained the basic understanding and experience with experimental methods in the Aeronautics Laboratory Course, they may continue their development through optional programs. Cadet summer research affords motivated students the opportunity to spend part of their summer, before senior year, at a government, industry or academic institution, either furthering the efforts initiated in the first class, or expanding to an entirely different area. Approximately 50% of students are able to take advantage of this opportunity. More motivated students, typically those who have validated some USAFA core course requirements, extend their depth even more with independent study courses, wherein for two or even three semesters they can extend their depth and understanding on a research topic.

Table 1. Current Projects

Project	Sponsor
A-10 Aircraft Surface Patch Investigations	USAF Ogden Air Logistics Center
Micro Air Vehicle Stability Analysis	USAF Research Lab/Munitions
Fighter-Sized Target	USAF Research Lab/Air Vehicles
Reusable Booster	USAF Research Lab/Air Vehicles
Rotax 914 Knock Assessment	USAF Research Lab/Air Vehicles
F109 Turbofan Flow Disturbance	Arnold Engineering Development Center
Cycloidal Wave Energy Converter	National Science Foundation
Tangent Ogive Vortex Control	Republic of Korea Agency for Defense Development
Orion Pilot Chute Aerodynamic Characteristics	NASA
Plasma Actuators	USAF Office of Scientific Research
Parachute Suspension Line Drag Analysis	US Army Natick Soldier Center

4. Computational Education

Similarly, the department has substantially revised its computational fluid dynamic curriculum to provide graduates with the skills necessary to perform such simulations. The Department has found that the cadets come to the Academy with relatively high levels of computer skills but very much lacking in the computer programming abilities necessary for success as the modern engineer. Unfortunately, the curriculum at the Academy is very much constrained by the overarching core that a programming course could not be added. The Department instead took the approach of adding computer projects into individual aeronautical engineering courses thereby weaving a computational thread throughout nearly the entire curriculum. Development of computer skills begins in the sophomore level thermodynamics course with basic Matlab programming in which the cadets learn basic operation, syntax and how to write simple “for” loops. In the junior level flight mechanics and aerodynamics courses, the cadets learn to write subroutines, import and export data, perform numerical integration and nested “for” loops as they work on projects like analyzing velocity data from the wake behind a cylinder to calculate drag, unsteady response to an impulsively accelerated wall in Poiseuille/Couette flow, and potential flow theory solution to flow over an airfoil.

The centerpiece of computational skills development is a spring semester junior level aerodynamics course which is designed to make the cadets "intelligent users" of advanced computational fluid dynamics codes. The cadets begin this course by utilizing a vortex panel method code to compare aircraft lift characteristics to wind tunnel and flight test data. They are then introduced to finite differencing and write their own code in Maltab to solve the heat and wave equations. The second half of the course is dedicated to teaching the cadets the four steps in the computational fluid dynamic solution process: geometry generation, grid generation, flow solution and post processing. The cadets utilize commercial software packages and a local parallel process computer system in the application of this four step process to solve for the flow around a 3-D inviscid wing and a 2-D viscous airfoil. This computational fluid dynamics course represents one of only a handful in the nation at the undergraduate level that is *required* by all aeronautical engineering majors in a program. The computational tread continues into the senior year where cadets apply these computational tools to analyze the aerodynamics of their aircraft designs in the capstone courses. Advanced CFD elective and independent research courses are also offered, giving cadets the opportunity to engage in sponsored computational research projects with a faculty mentor similar to experimental projects outlined above.

5. Additional Program Elements

Also of special note is DFAN's Flight Test Techniques course, a special semester-long immersion in the academic and operational aspects of aircraft performance testing. In this highly-competitive elective course, students practice flight test data collection and analysis methods. At the end of the semester, they visit the actual TPS facilities in California to validate their skills during USAF T-38 Talon supersonic trainer flights. Many aeronautics majors have gone on from this unique experience to graduate from an Air Force, Navy, or international TPS programs.[7]

6. Recognition and Awards

The Academy's overall engineering program is recognized consistently as one of the nation's top five undergraduate programs.[8] The aerospace curriculum in particular was recently rated as the second-best undergraduate program in the nation.[8] Furthermore, USAFA won the National Aeronautics Association 2001 Cliff Henderson Award for "significant and lasting contributions to the promotion and advancement of aviation and space activity in our United States and around the world."[5] The department has averaged 12 students enrolled in AE 499 with an average of 6 AIAA papers published per year. In the last three years alone cadets from the Department have been awarded first place twice, second place twice and third place three times at the AIAA Region V Student Paper Conference in addition to receiving top honors at the AIAA international student paper competition. This level of success can only be achieved through a concerted long term effort focused on building the necessary skills as well as instilling the proper mind set to perform independent research.

Despite having a reputation as one of the most difficult majors at the Air Force Academy, the Aeronautics Department continues to attract high numbers of talented students with between 60-80 majors per year. Even through this number of students represents only 6-8% of a typical Academy graduating class, they can hold as many as 20 of the top 100 slots based on overall order of merit. This high class ranking results in average of 15 graduate scholarships award per year including nationally competitively appointments to MIT, University of Washington and Rice. The cadets' active duty career fields are pre-selected prior to graduation based on class ranking and personnel desire. 50% of a typical graduating class of Aero majors will go on to pilot training with approximately 15% going into engineering or aircraft maintenance and the remainder into other specialized career fields. Surveys of the supervisors of recent graduates indicate that the in-depth and applied curriculum prepares the students well for whichever career field they end up serving.

7. Conclusion

The United States Air Force Academy has made, and will continue to make, significant and lasting contributions to the promotion and advancement of aviation and space activity in our United States and around the world. USAFA's Department of Aeronautics is an integral part of the institution, providing critical components of the academic curriculum while supporting the professional military officer training program in numerous ways. USAFA graduates have proven the worth of their education in numerous ways in the military and civilian spheres of influence. DFAN is proud of its contributions to aerospace power in these last four decades of a century of manned flight.

The combination of faculty, facilities and curriculum at the United States Air Force Academy offer a superb environment for collaborative aeronautical engineering educational research activities. In addition, numerous research activities sponsored by Department of Defense and NASA customers offer both sabbatical and postdoctoral education and research opportunities. As a result of the unique educational research opportunities associated with the Academy's aeronautical engineering, the Air Force Academy is well positioned to graduate and commission officers with the knowledge and skills to develop new technical solutions and prepared to serve and lead the United States' highly technical air and space forces.

References

1. USAF Academy Curriculum Handbook, 2010, p.2.

2. Snyder, Noel & Helen. Raptors: North American Birds of Prey. Voyageur Press, Stillwater, MN, 1997, pg 172.

3. Barlow, Douglas, Nowlin, Scotty and Bossert, David, Falcons Soaring: USAFA Department of Aeronautics Contributions to Aerospace Power During a Century of Manned Flight, AIAA 2002-0564, 40th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, 14-17 January 2002.

4. Tudor, Jason. "Academy staff, students streamline Gunships." Air Force Print News, Dec 14, 2001.

5. Johnston, Cheryl and Nettleblad, Tracy. X-38 Rudder Control and Speedbrake Performance Analysis for a Mid-Rudder Configuration. USAFA/DFAN Report 00-03. September, 2000.

6. 2001 Cliff Henderson Award Citation. National Aeronautics Association, 1815 N Fort Myer Dr #500, Arlington VA 22209

7. Scott, William B. "Cadets Introduced to Flight Testing," Aviation Week and Space Technology. January 17, 2000.

8. "Best Colleges." U.S. World News and World Report. September, 2010.

9. "Best Colleges." U.S. World News and World Report. June, 2001. http://www.usnews.com/usnews /edu/college/rankings/engineering/nophd/aero