Design and Implementation of a Computer Data Acquisition and Control System for a Portable Wind Tunnel as a Benchmark Task in a Senior Aerospace Engineering Laboratory Class

Thomas Hannigan, Keith Koenig, Bryan Gassaway, Viva Austin
Department of Aerospace Engineering, Mississippi State University

Abstract

Upper division aerospace engineering undergraduates have an introduction to the programming environment LabVIEW, data acquisition, control systems, transducer selection and calibration, and peripheral programming in their initial laboratory class. In the subsequent semester, the ability of the students to implement a complete data acquisition and control system (DACS) is tested by an assignment to develop and implement a LabVIEW program for an existing portable wind tunnel used for student orientations and classroom demonstrations. This assignment includes development of a program for control of the tunnel speed and angle of attack of an airfoil in the test section, and operation of a pressure scanning system, as well as presentation of airspeed, angle-of-attack, and airfoil pressure distribution in a user-friendly display. Calibrations of potentio-metric and strain-gage based instrumentation are incidental to the programming assignment, and serve as a review of hardware selection and integration. The standard parallel port is used for digital peripheral control, and a typical data acquisition card is used for logging transducer output. Only six laboratory hours are allowed for the development and testing of the program, in two, three-hour sessions. This paper details success in the development of the current assignment, done by pairs of students, as well as difficulties encountered when larger groups of students attempted to develop the same program in parts, to be assembled during the second lab class. The teaching of basic concepts in DACS is reviewed, and student understanding of those concepts is accurately gauged through the completion of this assignment.

Background Discussion/Motivation

The primary objective of the first assignment in class ASE 4721 is to determine if the students are in fact ready to proceed to more complex experiments. In their first course, ASE 4113, lab students are introduced to the fundamental processes of data acquisition and control systems necessary to conduct various experiments. In the second of this two-course laboratory sequence required of all upper division aerospace engineering undergraduates at Mississippi State University (MSU), those processes become incidental to conducting experiments. Though the conduct of this lab has its particular emphasis and objective in developing a control system for a portable wind tunnel, the principle objectives in performing this task are larger in scope. They include:

- review of transducer calibration, limitation, and use
- review of electronics and digital data acquisition
- review of digital control of peripheral devices
- review of LabVIEW for programming DACS
- readiness of students to proceed with DACS programming as merely incidental to lab experiments

If students are to properly correlate experimental data with theoretical predictions, an understanding of the methods used to sample data is required in order to be able to properly assess the differences that appear between theory and practice. There are also limitations of equipment that will establish precision of measurements, and factors under the control of the experimenter that may affect the accuracy of the measurements. Students are never allowed to generalize errors as being merely human factors or imprecise measurements, but rather must make every effort to identify and eliminate sources of potential errors. They must insure, for example, that they are sampling at an appropriate frequency and duration to insure that noise or unsteady measurements may be isolated. They must have a grasp of the associated physics prior to attempting measurement of laboratory phenomena for correlation with theory. It is essential to recognize when attempts to measure flow, for example, interfere with the flow field due to the size or placement of probes, or when the response characteristics of an instrument might lead to electronic aliasing or masking of the true conditions.

To impart these skills to the students, various transducers are calibrated using different measurement techniques, those transducers are then used in bench or wind tunnel experiments. They learn the basic principle of correlating a physical quantity with a measurable quantity. Temperature, pressure, force, and flow are all related to measurable quantities such as voltage, current, or resistance. Multi-meters, both hand-held and computer-controlled, and standard PC data acquisition boards are used to make measurements. An introduction to signal processing is conducted using analog-digital electronic trainers.[1] Students learn or reinforce necessary electronic knowledge and skill required to use computers for experiment control. This includes using canned programs for DACS, as well as development of DACS programs from scratch in the LabVIEW programming environment. Using the signal generators built into the electronic modules, and peripheral digital storage oscilloscopes[2] interfaced to each computer, signals of varying frequency, magnitude, and offset are examined. The digital oscilloscope displays and plots of samples recorded with the data acquisition card both show aliasing if the sampling interval and rate are not appropriate—the plots show how a waveform at a known frequency and amplitude can appear to be a completely different frequency, particularly if digital samples are made at a multiple of the signal's actual frequency. The students see that at sampling rates less than twice that of the true signal, the frequency cannot be reliably determined, and that rates of ten times the sampling frequency are adequate for determining the voltage magnitudes with fair precision. The limits of accuracy of the measurement system are illustrated, as are the effects of offset and noise.

Courses in electronics have recently been eliminated from the aerospace engineering curriculum at MSU[3], and as a result, most students require additional instruction in these areas. A particularly important topic for wind tunnel control is the method by which a digital controller actually communicates with peripheral devices. The students gain experience in this through a first semester laboratory module in which the standard PC parallel port[4] is used to make digital inputs and outputs that control a motor. The motor is turned on and off in response to the position of a switch that is digitally monitored. This illustrates the basic principle of isolating a control input from the peripheral action using computer programming to detect an external event. A digital input line tied to the center of a single-pole, double-throw switch is monitored by an assembly language program written by the students. The switch connects a high or low voltage to an input pin on the parallel port, and thus switches a memory bit between logical high and low values. The digital voltage output is at a pin connected to a specific bit of an output port. It is conditioned with appropriate external circuitry to buffer the computer against inadvertent voltage spikes or static buildup. The use of standard digital electrical components is reviewed, including resistors to limit current, diodes to guard against voltage spikes, transistors to switch current, and inverters to act as buffers. A high output eventually causes a bias on a Darlington transistor which allows a motor to operate. Thus by reading or writing to parallel port addresses, the program detects digital inputs corresponding to switch position, and produces digital outputs causing a motor to operate. Similar experiments had been done in the past with equipment such as the Hewlett Packard 3421A Data Acquisition/Control Unit[5]. The current use of the standard parallel port allows students to program using their own PCs, without the need to purchase additional hardware. The high level of detail in this laboratory activity provides the students with an excellent first experience with digital control systems.

The Benchmark Assignment

Although the essence of DACS programming and equipment setup is taught in the first semester course, care must be taken to insure that no student is left behind. The skills imparted in that first course are considered necessary and incidental to investigations conducted in the second laboratory course. In the subsequent semester, the ability of the students to implement a complete data acquisition and control system is tested by an assignment to develop and implement a LabVIEW program for an existing portable wind tunnel used for student orientations and classroom demonstrations. This tunnel will have been observed, and perhaps operated by students in earlier courses, so its use is familiar to the students. Some calibrations of its components will have been demonstrated in the first laboratory course. Several different versions of controlling programs will have been utilized, but only in a turn-key, executable format. The assignment to develop the DACS program is made in the context of an immediate necessity to develop a new program because of failure of the previous hardware or loss/corruption of the software. Having this and the additional motivation of developing a program to be utilized by lower division classes operating this tunnel generally leads to a strong desire for recognition among these upper division students.

This assignment includes development of a program for control of the tunnel speed and angle of attack of an airfoil in the test section, and operation of a pressure scanning system, as well as presentation of airspeed, angle-of-attack, and airfoil pressure distribution in a user-friendly display. The system consists of an open loop wind tunnel with a rectangular cross-section at the entrance that transitions to circular cross-section downstream of the test section, where it is mated to a DC-current turbine. The current to the turbine is controlled by manipulating the variable supply to an AC to DC converter with a small, computer-controlled, reversible DC motor. Mechanical limit switches insure that the variable control is not commanded outside its movable range, which would result in failure of the drive mechanism. The speed of air through the test section is monitored by the difference between a total pressure port and a static port in the test section wall. This dynamic pressure is plumbed to a mechanical airspeed indicator, and to a pressure transducer that produces a linearly-proportional voltage. By monitoring the voltage, and hence the speed in the test section, the power supply can be manipulated to affect the desired tunnel speed. An airfoil test specimen with pressure taps distributed along the top and bottom surfaces can be mounted in the tunnel. The taps for the airfoil and the tunnel total and static pressure, are plumbed to a bank of water manometer tubes, and to a scanning valve that can be cycled through the tubes, connecting each in turn to a second electrical transducer. The angle of attack of the airfoil in the test section can be controlled by a small, reversible DC motor in the same manner as the tunnel power, with feedback from a potentiometer geared to the motor shaft. This potentiometer produces a voltage linearly proportional to the angle of attack of the airfoil. The tunnel layout is shown below in figure 1.

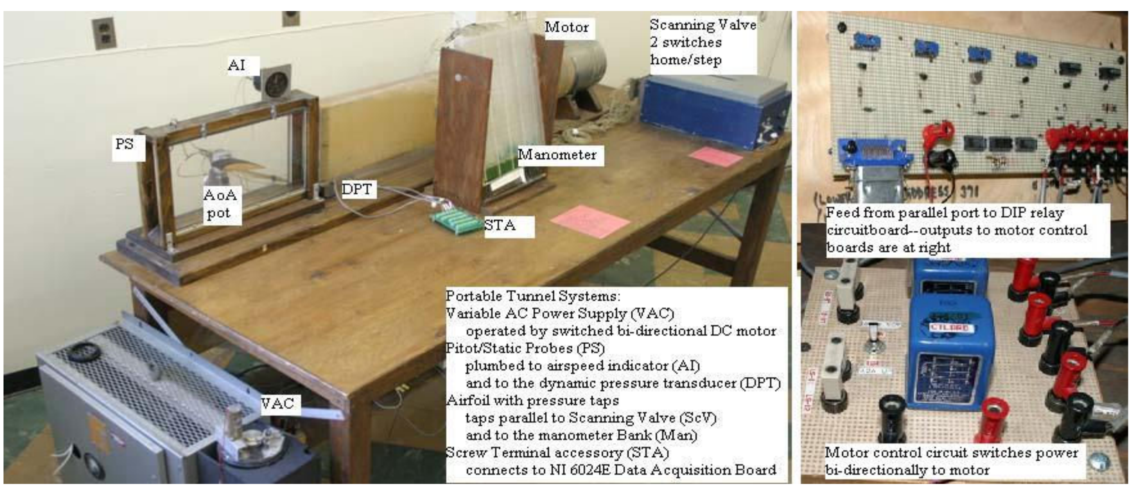

Figure 1: The portable tunnel

Calibrations of potentio-metric and strain-gage based instrumentation are incidental to the programming assignment, and serve as a review of hardware selection and integration.

Since the calibration of the angle of attack and pressure sensors have already been conducted as an exercise in the introductory lab, these are only conducted as necessary to insure that all students have a complete understanding of this critical requirement. The angle of attack is calibrated through the use of protractor and/or trigonometric measurements of a range of angles and associated potentiometer voltages. The velocity is controlled through the pressure transducer used to measure dynamic pressure, and that transducer is calibrated utilizing a slant-tube water manometer as a standard, with a vacuum source used to affect the pressure differential over the range desired. The same method is used to calibrate the pressure transducer used with the scanning valve.

The standard PC parallel port is used for digital peripheral control, and a common data acquisition card, currently an NI 6024E, is used for measuring transducer output. Logging of the signals is done for control purposes, and for informational display purposes during routine tunnel use. The actual control of the tunnel is accomplished by the output of high or low voltages on particular pins connected to an output port. When numbers are written to the port, those voltages are representative of the numbers, high or low. The voltages are buffered and wired across relays that close switches, either on a motor controller in the circuit depicted at figure 2, or across home or step switches on the scanning valve. Thus by writing different bit patterns to the PC memory address, as shown in the table below, control of angle of attack, velocity, and scanning valve is accomplished.

Hex address 378 [_ _ _ _](4 bits)	Hex address 37A [_ _ _ _](4 bits)
[0 0 0 1] decimal 1 velocity up	Not used
[0 0 0 2] decimal 2 velocity down	[0 0 1 0] decimal 2 step scanner
[0 1 0 0] decimal 4 AoA up	[0 1 0 0] decimal 4 home scanner
[1 0 0 0] decimal 8 AoA down	Not used

Figure 2: Control effects of numbers written to parallel port addresses Hex 378, 37A

All of the circuitry used to buffer the output data and close switches on the motor controllers was designed and constructed by undergraduate students of prior laboratory classes in individual research efforts. The programs originally used were written in BASIC[6], and used portable HP 75 computers and HP 3421A DAC Units. With the advent of the IBM compatible PC, standardized data acquisition hardware became cheaply available, and programs were re-developed[7] to use the parallel port for control and Metrabyte DAQ cards to read voltages from transducers. Testpoint[8] and LabVIEW[9] programs were similarly developed as those programming environments found their way into common use in the laboratory. These facts are given to the students, and hard copies of prior programs are available for review. The hardware has evolved through several generations of controllers, from using a Hewlett Packard Interface Link to the standard Hewlett Packard Interface Bus (HPIB/GPIB/IEEE488) to control switches, and several generations of early computers including HP, Apple, Atari, and Commodore computers. With the adoption of standard ports for input and output on all IBM compatible PCs, it was a natural evolution to utilize those ports for peripheral control.

Conduct of the Assignment

Only two three-hour sessions are allowed for the development and testing of the program. The first is devoted to pairing up individuals to work on the assignment, and after a short introductory briefing on the immediate need for a new program for the system, the students begin developing an algorithm for the DACS program. The student pairs are closely monitored, to insure that both students are participating in the program design and coding phase. A single student is not allowed to be the primary programmer while the other person observes only. Students paired at a computer station are instructed to switch "drivers" manning the keyboard. It has been observed that students generally work better if they simultaneously code on their own laptops or computers arranged so that they can both see the efforts of the other. Developing parallel programs guards against the inevitable computer glitches that cause programmers to often start over at square one! The student pairs generally have a very good outline of their program, and much of the initial programming done by the end of the first lab period. The lab teaching assistant is available during several off-lab periods to help with students who are having difficulties, and by the beginning of the second lab period, all of the programs are ready for live testing. If it is necessary to test components of a program, the tunnel setup allows testing of the velocity, angle-of-attack or pressure scanning systems independently. In fact, most of the students choose to create a sub-virtual instrument (sub-vi) for each separate action that can be used later in the overall program repeatedly. This not only insures that they know exactly how the external switches are manipulated, but also eliminates repetitive code from their main program. A typical outline of the program is given in figure 2, while the contents of a typical LabVIEW front panel are detailed in figure 3.

- On Program Start, Clear All Output Ports
  - Display Connections Message
  - Await Continue Command
- Obtain and Display All Reference Voltages
  - Dynamic Pressure Transducer Zero Voltage
  - Angle of Attack Potentiometer Zero Voltage
  - Scannivalve Transducer Zero Voltage
- Perform desired actions until STOP command
  - Change Velocity to that desired
  - Change Angle of Attack to that desired
  - Display Pressure Distribution
- On Stop Command
  - Return Angle of Attack to zero for subsequent runs
  - Command velocity decrease
  - Zero all outputs and terminate Program

Figure 3: Outline of Wind Tunnel Control Program

- Action Buttons
    - Program Continue Button
    - Change Velocity Button
    - Change Angle of Attack Button
    - Take/Display Pressure Data Button
    - Tunnel Shutdown Button
- Control Inputs
    - Desired Velocity
    - Desired Angle of Attack
- Digital Displays
    - Velocity
    - Angle of Attack
- Graphical Display Cp versus x/c Pressure Distribution
- Hidden Digital Displays/Arrays
    - Desired voltage for AoA, Velocity
    - x/c Array Data Array Cp Array

Figure 4: LabVIEW Front Panel Elements

A typical front panel constructed for this assignment is shown in Figure 5, while an example of the wire diagram programming is shown at Figure 6. All of the variables used by the front panel are grouped at left, and are global to all of the wiring diagram program structures. Local variables within the structures of the program are then pointed at those commonly used variables.

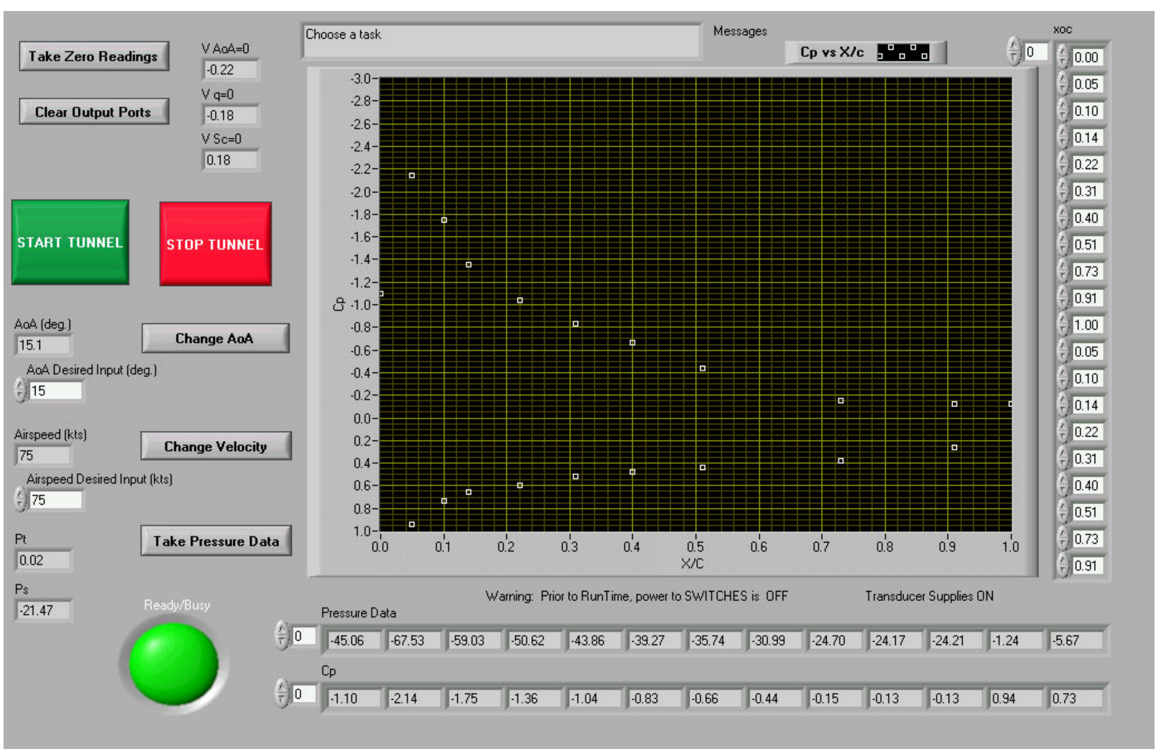

Figure 5: Front panel of LabVIEW program constructed for this assignment.

The students have had excellent success in the development of this assignment when it is detailed to pairs of individuals, with all programs completed successfully within the allotted time. Attempts to have six-person teams develop the program in the same time frame have not been as successful. In those efforts, three pairs of students divided up the tasks of controlling the velocity, angle of attack, and pressure measurement system independently, with the intention of combining the three programs into a completed package. However, the groups did not spend enough time detailing precise variable names and program structure, so the combination of their individual efforts into one program resulted in much necessary re-development. When it came to the program combination, only one or two individuals out of the larger group could work on the final program at a time, while two-thirds of the group paid less than full attention to the details. When the entire program is written by pair**s** of students, the parallel nature of many of the tasks allows the students to take full advantage of common variable names that make the task flow more easily, and the final product is much more cohesive and easier to understand and debug.

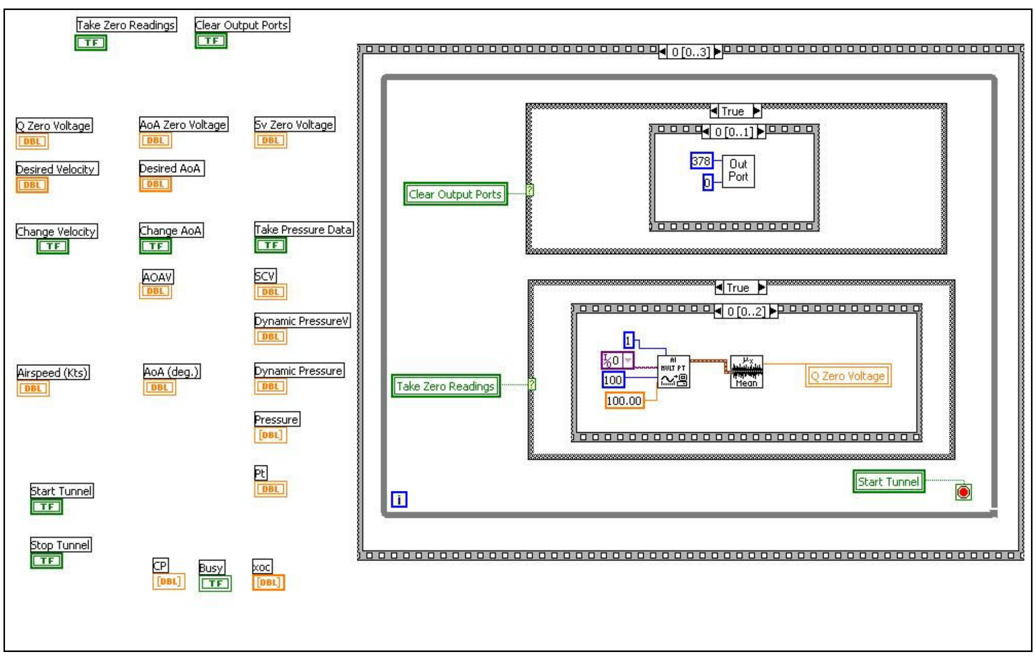

Figure 6: LabVIEW wiring example showing variables at left, initial structures at right

This assignment gives a good review of the basic principles of data acquisition and control systems programming, and the student understanding of those fundamental concepts is effectively observed through this exercise. Skills taught in the introductory laboratory course are reinforced and the confidence of the students in programming a complete system is increased. Since remaining exercises in the final lab course have a primary emphasis on the phenomena being observed or tested, the programming becomes merely incidental to task accomplishment. As a result of their experience with controlling the wind tunnel, the students are observed to respond much more favorably to pre-lab assignments requiring adaptation or development of new programs. They arrive at lab class ready to implement their solutions, and the use of their own programs rather than black-box or turn-key programs insures that they are more familiar with the data collected, and any limitations of their own programs. This aids in the analysis by increasing their background understanding of the experiments.

Assessment and Student Feedback

It had been noted that students completing an introduction into computer data acquisition and control systems programming during the first laboratory course, ASE 4113, experienced difficulty in programming solutions that were intended to be merely incidental to the conduct of further lab experiments in ASE 4721. Students seemed unready to apply those principles learned in the first course, and the programming solutions for DACS consumed the attention of the students, and shifted their emphasis away from the intended focus of a particular lab exercise. By reviewing principles of transducer calibration and use, electronic data acquisition, and digital electronic control of peripherals, the students were reminded of the incidental nature of DACS programming. Additionally, their knowledge of those principles was reviewed and reinforced, and their confidence in application of those principles was boosted. When there was no such review, exit interview comments from students completing the lab sequence included remarks such as “I thought that the focus of the labs was on aero engineering, but I felt overwhelmed by the details.” In retrospect, that same student remarked, “the programming requirements were valid and necessary, but I didn’t realize that at the time.” When this review assignment was broken into three parts to be completed by pairs of individuals, who would later combine all parts into one program, the central complaint was that “the main problem to be overcome was communication, and putting together disjointed programs proved to be an exercise in futility and repetitive programming.” However, when this program was completed in its entirety by a pair of individuals, feedback was universally positive. As one student observed, “It was a good review of nearly everything we learned in the first lab. After putting together this program, I was able to easily develop codes to do lesser tasks later on.” Another commented, “I really liked being able to show that I could program and implement a complete DACS program. I felt that all of the later programming was much easier to do after that.” Although the teams of six students were eventually able to program a solution, it was always at the expense of reprogramming parts to insure compatibility, with a resulting waste of time and negative feelings for the individuals whose code was rewritten. Programming the solution by pairs of students resulted in 100% success by the entire class, in fewer laboratory class hours.

Conclusions

In the past, having students develop hardware and software for control of a portable wind tunnel as a special topic or senior seminar project has provided a continual update of a portable wind tunnel system. This system was effectively used in classroom demonstrations and student lab activities for fluid mechanics and aerospace engineering classes. The present requirement of all ASE 4721 laboratory students to design and implement a complete data acquisition and control program for this wind tunnel system is an effective tool for gauging readiness of those students to move beyond rudimentary training received in ASE 4113. This task provides good motivation to all upper division students who are required to take these courses, and improves their confidence in their abilities to perform incidental programming. Using a complex benchmark assignment reviews those principles intended to be learned by all aerospace engineering laboratory students, and evaluates their readiness to move to more detailed experiments with emphasis on DACS programming removed.

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Biographical Information

THOMAS HANNIGAN
Thomas Hannigan is an Instructor of Aerospace Engineering and Engineering Mechanics. He received his BS and MS degrees from Mississippi State University. His interests include introductory engineering mechanics, airplane flight mechanics, and he coordinates laboratory activities for the department. He holds FAA Gold Seal Flight Instructor Certification for single, multi engine and instrument airplanes.

KEITH KOENIG
Keith Koenig is a Professor of Aerospace Engineering. He received his BS degree from Mississippi State University and his MS and PhD degrees from the California Institute of Technology. Prof. Koenig teaches courses in aerodynamics and propulsion. His research areas include rocket and scramjet propulsion and sports equipment engineering.

BRYAN GASSAWAY

Bryan Gassaway is a lecturer and PhD student in the Aerospace Engineering Department. He received his BS and MS degrees from Mississippi State University. He teaches astrodynamics and has taught courses introducing aerospace engineering, flight mechanics, stability and control, structures, propulsion and astrodynamics, as well as assisting with the laboratory classes.

VIVA AUSTIN

Viva Austin is a graduate teaching assistant in the senior aerospace engineering laboratories. She obtained her BS degree in aerospace engineering from Mississippi State University, and is currently enrolled as a candidate for a master of science degree. She assists in teaching upper division laboratory classes as well as assisting in the conduct of laboratory activities for three lower division introductory classes.