Session Number 3159

Modernizing a Legacy Wind Tunnel: Hanging Onto and Letting Go of the Past

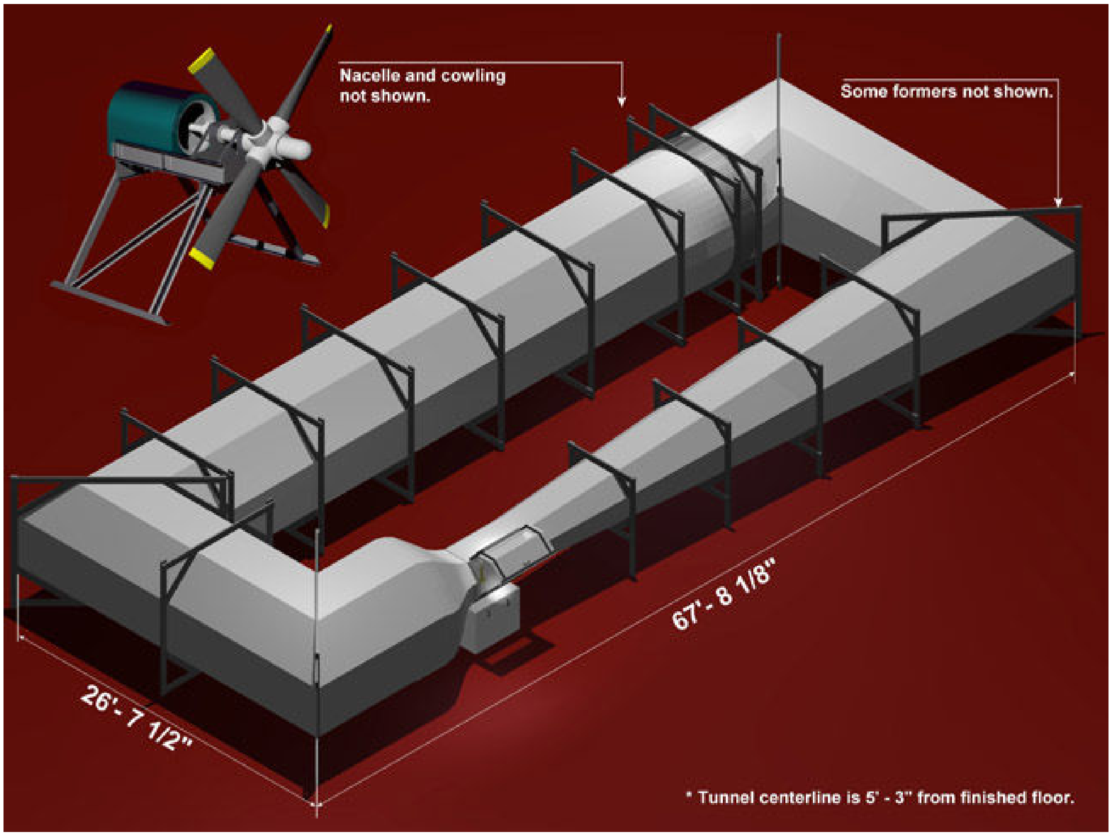
Thomas Hannigan, Keith Koenig, Bryan Gassaway, Viva Austin
Department of Aerospace Engineering, Mississippi State University

Abstract

A medium-scale, closed-circuit subsonic wind tunnel facility used for undergraduate aerospace engineering laboratory experimentation and research represents a substantial investment in resources. The control systems and data acquisition systems must evolve so that the age of the facility does not prejudice researchers serious about their academic endeavors. The evolution of such a system is detailed, including plant development, improvement and modernization of its systems, and data acquisition and control systems (DACS) programming. Individual student research projects that contributed to the continued evolution of the facility are described, and the usefulness of maintaining such a facility as a training tool in dealing with legacy systems is discussed. Through five distinct iterations of programming environments and hardware exchanges, some integral components have remained untouched through years of refinement, due to their robust initial design and continued reliable service. Recognition of system limitations and capabilities is essential to successful upgrade of systems such as these. The implementation of a user-friendly interface for control of the wind tunnel and selection of various data acquisition options is detailed, and the development of the current LabVIEW program is discussed. The importance of being able to re-equip and reprogram DACS instrumentation and presentation is presented as being essential in maintaining a positive image of the research laboratory.

The Early Tunnel

Research facilities and undergraduate teaching laboratories are a necessary part of any aerospace engineering programs physical infrastructure. Academic faculty members are encouraged to continue research in their primary interest areas, and indeed such research is a requirement for those at research institutions. Large-scale laboratory systems such as wind tunnels are not simply static facilities. A medium-scale, closed-circuit subsonic wind tunnel facility used for undergraduate aerospace engineering laboratory experimentation and research represents a substantial investment in resources. The laboratory building housing a wind tunnel is often constructed around such a facility, and support facilities are sized and located accordingly. The facility housed in Patterson Hall at Mississippi State University (MSU) was moved into the building upon completion of construction in the 1960s. Wood and machine shop facilities were located adjacent to the tunnel to provide research and educational support. The tunnel has an octagonal cross section throughout its closed loop wooden structure, except for the plane of the propeller, where it is tapered to be circular. The four-bladed, variable pitch propeller is nine feet(~2.75 meters) in diameter, and is driven by a 75 horsepower(56kW), 3-phase electric motor at 1200 rpm.



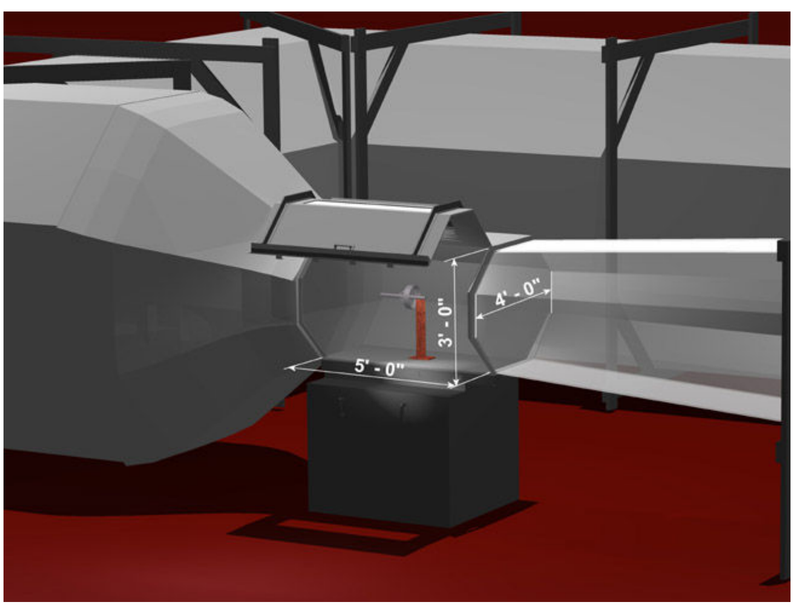


Figure 1: Wind Tunnel Plan View and Test Section

The pitch of the propeller blades is controlled by a 4096:1 geared 24V DC motor in the propeller hub operated through a set of slip rings with electric brushes.

As shown in Figure 1, the layout of the tunnel is rectangular, with faired corners equipped with carefully designed turning vanes. The outer diameter tapers through a six-feet (2 meter) long convergent section of 10:1 ratio, to the octagonal test section which measures 3’ high by 4’ wide by 5’ long(.9 by 1.2 by 1.5 meters). Downstream of the test section the tunnel expands at approximately 4 degrees divergence, over a total length of more than 50 feet(15.2 meters). The test section is limited to 160 feet per second(~50 meters per second) maximum velocity for continuous operation, due to current demands of the electric drive motor at higher speeds. The tunnel has been operated to 200 feet per second (~60 meters per second) for short durations. A photograph of the view downstream through the test section is shown at Figure 2. A 1:25 scale aircraft model is mounted on the vertical support shaft, or sting, which is connected to the external balance which is in the housing beneath the test section as shown in Figure 2. Note the turning vanes downstream of the diverging section of the tunnel.

Figure 2: View Downstream

In his 1984 thesis,[1] Iles discusses the wind tunnel facility in depth, including the control system used when the tunnel was automated in the 1980s. The manual starting lever was operated with electrically activated pneumatic relays controlling pressure to a piston that moved the lever to the start and run positions. The lever was held in the run position by an electromagnetic relay, and was spring loaded to the stop position upon release of that relay. The first of a series of computer controllers was a Hewlett Packard single line computer, communicating through a Hewlett Packard Interface Bus to a switching unit that multiplexed various data acquisition channels to a digital multimeter. Data storage via an 8 inch floppy drive was accomplished via a Hewlett Packard Interface Link, a two-wire serial connection. Immediate analysis was affected by using strip-chart recorders to record analog data, and hard-paper plots were produced by an HP plotter. All through the 1980s the use of multiple computers for data acquisition and analysis was pursued through a series of projects, as new platforms emerged and the university participated in various educational programs that provided Apple and IBM compatible computers. Electrical engineering and aerospace engineering senior seminar projects and master’s thesis projects concentrated on developing and applying data acquisition and control methods to current topics.

Figure 3: Tunnel Test Section Access Port

Access to the test section is gained through an access door that opens to provide complete freedom to work on models in that area. The power supply banks at left are for the transducers in the 6-component force balance housed beneath the test section. Models are connected to the external balance through the sting as shown in Figure 3.

The tunnel has been used for many such projects over the past four decades, including studies associated with aircraft development at the Raspet Flight Research Laboratory. Boundary layer studies, flow across cavities, flow around various shapes including cylinders and ogive bodies, as well as detailed studies of flow over various land and air vehicles have been documented through the years in a steady stream of masters theses and individual senior seminar project reports. Successful lift and drag studies have been conducted on items as diverse as sports balls, architectural models, home ventilation components, and grape vine sections. Laboratory experiments conducted in the tunnel have been a staple of undergraduate education, including boundary layer flow on flat plates, pressure distribution around airfoil sections, stability derivative analysis of flight models, and flow studies around various geometric shapes. Models studied by students for individual projects have included airfoils, remotely controlled aircraft, vehicles, and flying toys. Methods used for recording pertinent experimental data have evolved over the years from manually recording or photographing indicators to strip-chart recorders and analog recorders, to digital sampling and recording capabilities. During the 1980s refinements and the adoption of standards in digital communications technology led to the selection of an HP Vectra, IBM compatible computer using the General Purpose Interface Bus (GPIB, formerly HPIB), as the basis for the first full-screen computer controller for the tunnel. All of the software previously developed for the single-line computers was immediately executable on this new system. Nearly every component of the systems originally used had been replaced or upgraded several times in getting to this configuration. This tunnel, its digital control systems and programs were inherited by a new generation of laboratory staff upon retirement of a group of long-time faculty and laboratory staff in 1990. A legacy of continuing efforts to improve upon the facility was thus passed on to engineers immersed in a decade of rapid progress into the current computer age.

Tunnel Development

Particularly during the past decade, as digital technology and the personal computer became ubiquitous in the laboratory setting, the control of the tunnel was completely automated and data acquisition systems were combined with or controlled through computer programs. Since all new faculty candidates and many prospective students and their families often toured the laboratory facilities as part of their departmental orientation, it became increasingly important to insure that the wind tunnels presented an up-to-date image of the research being conducted. The control systems and data acquisition systems had to evolve so that the age or appearance of the facility did not prejudice researchers serious about their academic endeavors. Students and their families also needed to be favorably impressed with the undergraduate student research efforts being conducted. Since many high school students associate aeronautical studies with the design and testing of airplanes, they were keenly interested in the wind tunnel facilities from their first campus visit. This subsonic tunnel has thus been a point of focus in the undergraduate laboratories, and a concerted effort has been made to keep its systems up-to-date. The first twenty years of use of the tunnel saw the transition from manual control and rudimentary methods of acquiring data to using the first control units and computers. This progress was steady and continuous, and followed the state-of-the-art in the development of the first effective digital control system based on an IBM compatible computer. Evolutionary efforts continued to bring this legacy wind tunnel system into the present age.

There was no quantum leap in the progress from that first complete digital system to the present, and in fact that progress developed through at least five distinct stages. First, an HP Vectra computer, which ran the HP Basic environment upon startup, and provided control through its GPIB interface, was replaced by a fully IBM compatible PC. That PC contained a measurement co-processor board within it that allowed the HP Basic environment to run on independent hardware. Secondly, other data acquisition equipment rapidly became available in standardized formats and various interface bus varieties, and high speed data collection and analysis became possible. With the next generation of computer, data could be collected from two independent systems within a single computer, and streamed to disk for storage at very high rates. This allowed study of non-steady flow conditions and recording of real-time data for off-line detailed analysis. The Intel processor speeds were doubling and redoubling their speeds, with similar advances in digital recording hardware, and the relatively slow GPIB was eclipsed by direct memory addressing and high-speed data streaming over the newer bus architectures. In this third phase, two separate computers were typically used, with one providing control of the tunnel itself, and another for recording of high speed data from more capable ISA bus data acquisition cards. The first generation measurement coprocessor board was rapidly supplanted by even more capable derivatives, and the ability of communicating between the main processor and the coprocessor board allowed the recombination of DACS programming from two or more computers into a single platform. The leap into the Pentium age and graphical programming environments led to the next stage, and the development of a Testpoint program that used an IEEE 488.2 interface card to communicate to those instruments formerly addressed via the GPIB on the measurement coprocessor card, and high speed data acquisition via boards plugged into the ISA bus. When the engineering college adopted a computer initiative that included a site license for LabVIEW, this led to the fifth major software and hardware revisions. This included the development of ever more user-friendly LabVIEW program interfaces, and easier programming within LabVIEW with a switch to National Instruments DACS cards using the PCI bus.

The wind tunnel primary startup and velocity control subroutines have remained virtually unchanged since their first development in a study of the initial digital control system with transport and time delay. Those subroutines have been translated into newer programming versions and graphical programming environments, but with the exception of refinement of characteristic time constants of the system response, little substantive changes have been made to the original algorithms. The switches contained in the HP

3495A, multiplexing unit have continued to operate flawlessly for over 20 years. They have been controlled by programs running on HP 75 portable computers with commands translated from an HPIL link to the HPIB interface of the DAC unit. Similarly, the actual hardware switches used for startup have been operated with HP 3421A data acquisition and control units via and HPIL interface. With the implementation of an HP 9835B single-line computer with an HPIB interface, the 3495A unit was hardwired into a configuration that has remain virtually unchanged for two decades. These systems were not only used for control of the subsonic tunnel, but also for control of two separate supersonic tunnels, and many projects that were initially aimed at one or the other of the subsonic or supersonic tunnels ended up in changes to the programming used for each. In addition to using an HP 3455A DMM to measure voltages on various channels, a digital pressure scanning system, the Pressure Systems Inc., DPT 6400, was added to the system. This programmable device itself went through several stages of upgrades to its separate PC internal interface. This scanner system was programmed through the GPIB with a standardized set of commands, and communicated data streams to the PC on demand. Although the wind tunnel and its control system referred to here as a legacy was not actually an original being handed down, but rather a work in progress at any moment in time, there was a distinct sense of having a complete system after the addition of the pressure scanning system to the original Vectra-HPIB-based system.

The ability to scan 32 or 64 channels of pressure data simultaneously allowed the use of wake rakes to collect downstream flow fields from objects in the tunnel test section, as well as the collection of axial or other distributions of pressure taps. Thus the system was useful in conducting flow studies including flow around airfoils as well as other diverse objects. Known discrepancies with finite data sampling of pressure flow fields such as the movement of the stagnation and peak pressures associated with airfoil pressure distribution led to the development of programs for data smoothing. The advent of easily programmed full-screen graphics allowed for on-screen study of data, and led to graphical interaction with data sets for a more effective flow analysis. Faculty and graduate students spent a great deal of time developing a series of subroutines that could be integrated into programs used in the undergraduate lab for data analysis, curve-fitting, and plotting, both on-screen and with pen plotters. Those efforts eventually led to the development of terminate-but-stay-resident (TSR) programs for data analysis, rudimentary background high-speed data acquisition and plotting, to avoid the problems associated with integrating hundreds of lines of repetitive coding into programs the students used in laboratory exercises. All of those efforts were supplanted by the integration of high-speed data acquisition and fundamental signal processing functions built into the newer graphical programming environments. The communication with the pressure scanning systems improved dramatically with the advent of the internet age, and the ethernet communications protocol. The latest PSI system capabilities included a very easy interface to DACS programs through a complete library of standard graphical programming modules for LabVIEW.

A six-component external force balance system was developed concurrently with the development of the initial data acquisition and control systems, and this strain-gage based force balance provided very good resolution of forces and moments for study of many wind tunnel models. That system has only required a periodic recalibration and adjustment to provide reliable experimental data through years of conducting classic experiments with semi-steady state conditions. Due to the low speed of the original measurement system, the load cells of the original balance are often monitored through the use of high speed DACS cards to capture transient or non-steady state phenomena that heretofore were unavailable. Detailed analysis of vibration modes of the balance itself became possible, and critical velocities or frequencies of operating models could be determined. Prior to these studies, several experiments had gone awry and equipment was damaged beyond repair, for example, when oscillations of the balance sting at a fundamental frequency led to excitation of propeller whorl and failure of a propeller shaft. Such phenomena could not even be observed with the naked eye until the failure mode was initiated.

Faculty who were directing individual student research projects were primarily responsible for the steady improvement and modernization of the wind tunnel. The continuing development of analysis programming tools, coupled with the refinement of hardware, required a forward-looking attitude in leading individual student researchers to accomplish tasks in a timely manner. The laboratory coordinator regularly met with other faculty members to identify projects suitable for special topic, senior seminar, or master's thesis assignments. This development of a project list was effective at insuring that a number of students received real-world exposure to the problems associated with interfacing new equipment, extending capabilities of equipment already in place, and the modernization of a legacy system. This illustrated an important overall objective of the engineering curriculum, that of impressing the students that there is a need for lifelong learning. This point was easily illustrated by simply detailing the changes that were necessary to keep this facility evolving, so that its usefulness would be maintained. In fact, maintaining such a facility as a training tool in dealing with legacy systems is, in and of itself desirable. Actually assisting in the development of programs to interface new equipment for a large tunnel, or translating the entire DACS program into a new environment are tasks that parallel those assigned to capable experimental engineers. The accomplishment of such tasks during the undergraduate and graduate educational experience must surely produce engineers motivated to assume such responsibilities once they graduate.

Through five distinct iterations of programming environments and hardware exchanges, some integral components have remained untouched through years of refinement, due to their robust initial design and continued reliable service.

Figure 4: HP 3455A DMM/9535B Multiplexer

The HP 9535 switching unit (Figure 4) and all of the electromagnetic relays associated with the startup/shutdown of the tunnel, and control of the propeller pitch for setting velocity are still operated through the same HPIB, albeit now classified as an IEEE488.2 interface. A series of interface boards were purchased at one point to operate the tunnel through a PCIP interface, including modules for scanning, multiplexing and oscilloscope functions. Before programming was complete for those systems, a switch to a graphical programming environment capable of utilizing the older units, but in a much more user-friendly manner, made the switch to the PCIP hardware unnecessary. Those interfaces would not have extended functionality beyond that of the existing hardware, but in fact would have reduced the number of available channels of data/control signal switching. The HP 3455A digital multimeter (Figure 4) used has speed and resolution proven suitable for control of the tunnel, and additionally, it can be operated manually independently of the computer system for verification of subsystem operations. Over the past decade the unit has twice suffered component failure due to overheating, but the addition of control-room air conditioning and auxiliary cooling fans have extended the life of this DMM greatly. Recalibration of the load cells associated with the force balance, and recalibrations of the meter itself have shown that this device continues to give accurate and repeatable readings of resistance and voltage values from those load cells.

The Current System

Recognition of system limitations of existing equipment, and increased capabilities associated with upgrades are essential to identifying paths to successful upgrade of systems such as these. In the current economic environment, combining system upgrades with proposals for new research or special funding has been critical to attaining new computer equipment. Such combinations have resulted in improvements to the wind tunnel facility in particular, including the acquisition of a two-axis laser Doppler velocimeter, and a of hot-film anemometers and probes. This equipment insures that the students can be exposed to state-of-the-art, precision measurements during their undergraduate education. The acquisition of such supporting equipment, and the continued maintenance of good woodworking and metalworking facilities have helped to insure that the facility is ready to give the students a meaningful laboratory experience.
The latest program developed for wind tunnel operation by students as new as first semester freshmen represents the culmination of work accomplished by many students, over several years.

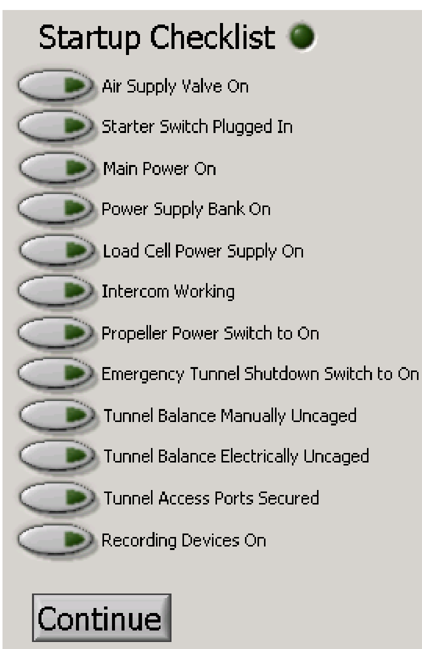


Figure 5: Checklist

The components of the LabVIEW program are illustrated in the following description, which details the contents of the graphical interfaces used for control of the wind tunnel and selection of various data acquisition options.

The Pre-startup Checklist Panel (Figure5) contains a step-by-step checklist of all pre-start actions, including air and power supply configuration as well as communications system and recording/control systems readiness.

The Initialization Panel (Figure 6) allows for changes to default transducer slope values, and allows for inputs of reference pressure values, to correspond with reference voltage values obtained from transducers. The progression of the program is sequential until the main tunnel run panel is displayed, then a case structure is followed, as shown in Figure 7. Note that the loop for Emergency Stop runs in the background continuously.

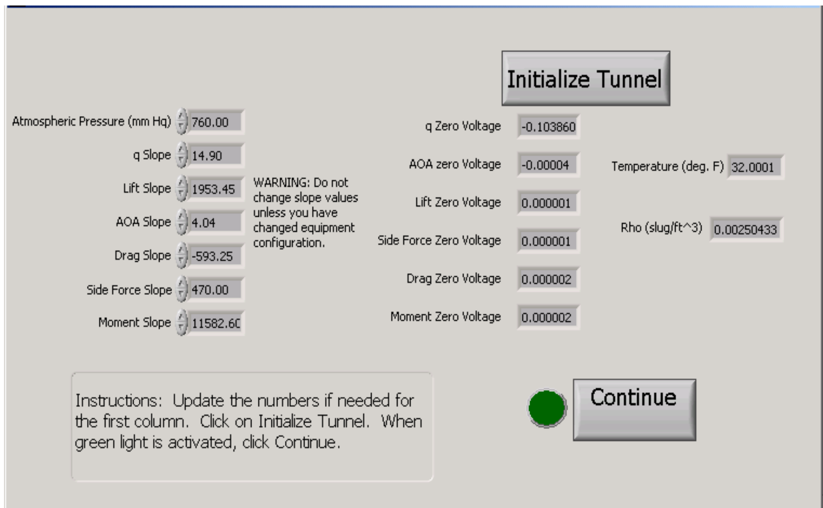


Figure 6: Initialization panel

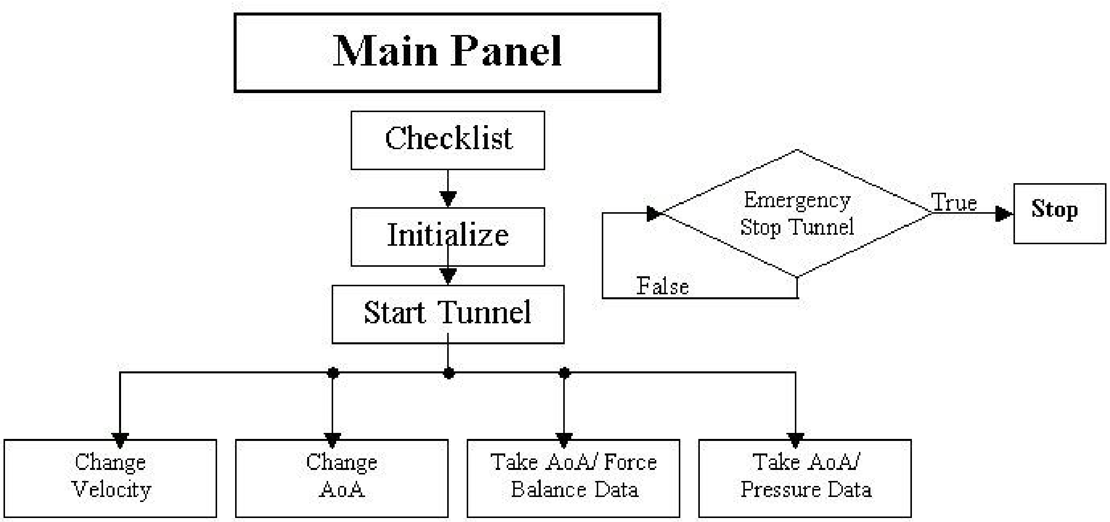


Figure 7: Flowchart of the Main Tunnel Run Panel

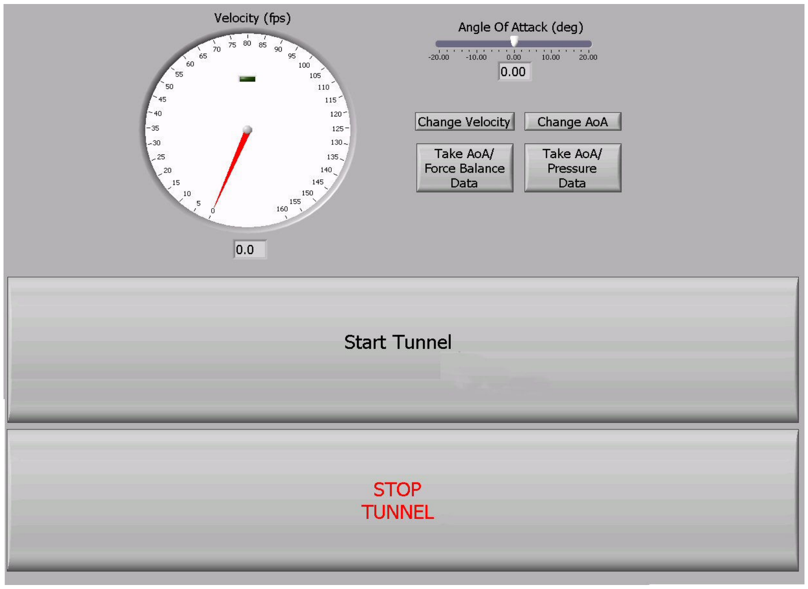


Figure 8: Main Panel

The Main Tunnel Run Panel (Figure 8) allows initial startup only if the checklist/initialization panels are completed. It allows for direct change of velocity or model angle-of-attack, or choosing of sub-panels for collecting force balance data and the acquisition with or without pressure scanner data. Prominent buttons allow for tunnel start and tunnel shutdown and program termination.

The Take AoA/Force Balance Data acquisition panel allows change of velocity or angle of attack, allows emergency shutdown, as well as single point data or multi-point data collection and display. Velocity, temperature, density, angle-of-attack, lift, drag, side force, and pitching moment are calculated and displayed. This panel allows for data save or append to an existing comma delimited file. For multiple data points, a range of angles-of-attack and selection of the desired angle increment are all that are required to initiate an automatic sequence of data acquisition and angle-of-attack control.

Each line of the resulting multiple point data file is in the same sequence as for a single data point. This panel also allows termination of the program on emergency shutdown, or exit to main program.

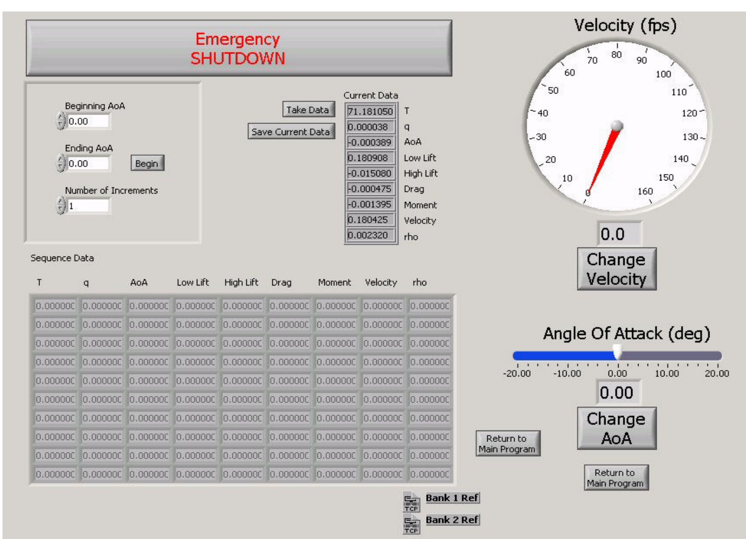


Figure 9: Force Balance with Pressure Data Acquisition

Similarly, the Force Balance with Pressure Data Acquisition Panel (Figure 4) also allows change of velocity or angle-of-attack, emergency shut-down, and single point data collection. It displays single point data on screen plus an array of pressure data (32 channels). It allows for data save or appends to existing comma separated values files. Multiple data point collection over a range of angles of attack are handled in the same manner discussed previously. Block diagrams of the airspeed and angle of attack data acquisition and control sub-programs are given below in Figure 10. Note that the tolerance switch remains closed until the tolerance is attained for both angle of attack and velocity.

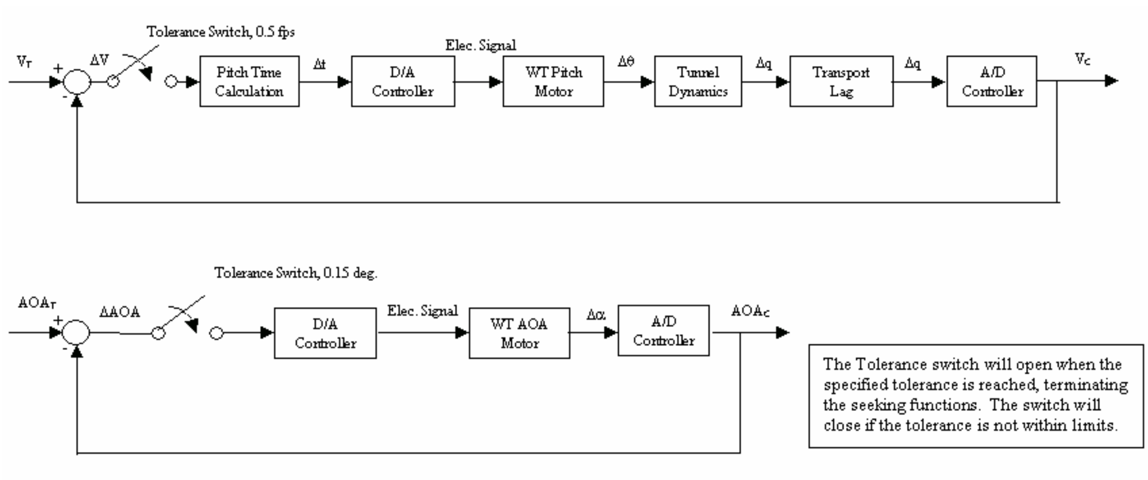


Figure 10: Velocity/AoA Block Diagrams

The importance of being able to re-equip and reprogram DACS instrumentation and data presentation from experiments is essential in maintaining a productive research laboratory with a positive image. As each successive group of student researchers have extended the capabilities of previous programs, their collective product has been nothing short of impressive as the control programs used have always been up-to-date. At the present time, we have preserved the last several generations of control computers and programming, so that students can experience the rapid progress over the past few years first-hand. As each system is used to control tunnel functions, the improvements that have been made, particularly in real-time signal processing and data presentation, are readily apparent.

In the near future the digital multi-meter and multi-plexer will be replaced, and the external balance will be supplanted by a robotic arm and internal stings for models. Later, when the propulsion system is replaced with a digitally controlled drive and fan, the tunnel replacement will be complete. This will most likely coincide with the renovation of the building that was built to house this system. Consideration is even being given to returning the tunnel to its early open loop operation, perhaps with an "open test section". Then its legacy will only be apparent in the shelves full of bound reports reflecting the collective and continuing efforts of the many to keep this legacy tunnel alive and healthy.

Conclusions

Periodic reprogramming of wind tunnel data acquisition and control systems is necessary to maintain and extend system capabilities. The Mississippi State University wind tunnel system has been successfully upgraded multiple times over a span of several decades. Each upgrade activity has provided significant educational opportunities, both for the students directly involved in the upgrade and for the students that followed. The lessons taught by these activities could never have been learned through operation of turn-key facilities. Perhaps this will be justification for preserving this facility, or at least for continuing to maintain several generations of its programs for a more effective learning experience.

Bibliographic Information

1. Hester, L.R., et al., "Wind Tunnel System Files: A collection of system descriptions, electrical schematics, drawings and notes", Patterson Lab Archives, Mississippi State University, c1980-1985
2. Iles, R., "An Investigation of a Digital Control System with Transport and Time Delay", MS thesis, Mississippi State University, 1984
3. Bridges, D., "The Development of a Boundary Layer Measurement Experiment", Senior Seminar Report ASE 2712, Mississippi State University, 1985
4. Fugate, M., "Working Hardware and Software for Communications Between Apple III and Hewlett-Packard Computers", Special Topic Report ASE 7003, Mississippi State University, 1986
5. Messer, B., "Control Loop Response Characteristics of the Supersonic Wind Tunnel", Senior Seminar Report ASE 2712, Mississippi State University, 1987
6. Burchak, R., "A Least-Squares Cubic Polynomial Spline Fit Algorithm for Data Smoothing", MS Thesis, Mississippi State University, 1987
7. Godwin, S., "Investigation of the Boundary Layer Near the Leading Edge of a Flat Plate at Zero Angle of Attack", Special Topic Report, Mississippi State University, 1987
8. Podbielski,C., "Development of a Real Time Data Acquisition and Control Program", Senior Seminar Report ASE 2712, Mississippi State University, 1989
9. Hannigan, T., "Analysis and Development of a Computer Controlled High Speed Data Acquisition and Control System for a Blowdown Supersonic Wind Tunnel", MS Thesis, Mississippi State University, 1990
10. Arellano-Gomez, M., "Integration and Refinement of Multi-Computer Data Acquisition and Control Systems Programming Into a Single-Computer Application for a Flat Plate Boundary-Layer Study With a One-Component Hot Film Anemometer", MS Thesis, Mississippi State University, 1993
11. Gross, J., "Development, Implementation, and Refinement of Hardware and Software for the Investigation of Two Dimensional Flow Fields With an X-Array Hot-Film Anemometer", MS Thesis, Mississippi State University, 1994
12. Caldwell, D., "Adaptation and Development of Wind Tunnel Data Acquisition and Control System with LabVIEW", Senior Seminar Report ASE 4113, Mississippi State University, 1998
13. McAllister, B., "Subsonic Wind Tunnel Data Acquisition and Control Program [Development, Testing, and Refinement with Testpoint]", Special Topic Report ASE 4004, Mississippi State University, 1999
14. Sebens, J., "Subsonic Wind Tunnel Data Acquisition and Control Program [Development, Testing and Refinement with LabVIEW], Special Topic Report, ASE 4113, Mississippi State University, 2000

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.