Supersonic Research Facilities and Opportunities at the United States Air Force Academy

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Abstract

The US Air Force Academy (USAFA) has one of the best-equipped academic aeronautics laboratories in the world. Among the many wind tunnels and test facilities housed in the USAFA Aeronautics Laboratory is a high speed blowdown facility called the Trisonic Wind Tunnel. In addition, a new Mach 6 Ludwieg Tube is currently being designed and will be online in May 2012. Substantial research opportunities exist for graduate, post-graduate, sabbatical, and exchange researchers, developing the capabilities of the Ludwieg tube and making use of the Trisonic Tunnel's well-developed force measurement and Schlieren photography capabilities. An example of such collaboration is the current development of the Background Oriented Schlieren capability.

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] 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. They 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 a weapons system operator, technical expert, specialist or graduate student.

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). 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 supported by approximately 30 laboratory and administrative staff 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 for a total of 147 required graduation hours.[1]

During the past decade, the Aeronautical Engineering Department has purposefully transformed its programs 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.

A critical component of the aeronautics major’s education -- hands-on research and development -- occurs in the DFAN Aeronautics Laboratory. The Laboratory is a 80,000 ft^2 ($7432m^2$) 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. The laboratory also includes two computer-based design classrooms and a complete machine shop. Research takes place under the guidance and leadership of the Director of the Aeronautics and Research Center. The Director’s efforts ensure that every cadet is involved in a real-world customer research project. These efforts are complemented by a robust computational capability (Modeling and Simulation Center) added in the last decade through the USAFA’s High Performance Computing Initiative. The Center’s Director likewise ensures cadet opportunities through interdisciplinary research in unsteady, turbulent computational fluid dynamics. In the labs, cadets benefit from working alongside experienced faculty members and technicians. Working as a team, the cadets and their instructors make significant contributions to real-world research, development, and operational programs sponsored by the USAF, NASA, and other DoD, civilian, and educational agencies.

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 Test Pilot School (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.[2]

The Academy’s overall engineering program is recognized consistently as one of the nation’s top five undergraduate programs.[3] The aerospace curriculum in particular was recently rated as the second-best undergraduate program in the nation.[4] 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]

2. USAFA current high speed facility

The current high speed facility at the US Air Force Academy is the Trisonic Wind Tunnel (TWT), which is a blow-down facility capable of a Mach number range for M = 0.14 to M = 4.5 and a run time of up to 7 minutes, depending on the Mach number (see Figure 1). For supersonic Mach numbers, fixed nozzle blocks for nominal Mach numbers of M = 1.4, 1.7, 2.0, 2.5, 3.0, 3.5, 4.5 are available (the actual Mach numbers computed from stagnation and test section conditions are M = 1.39, 1.68, 2.02, 2.48, 2.98, 3.47, 4.38).

Figure 1: USAFA trisonic wind tunnel.

Supply air is compressed up to 600*psi* by a two stage compressor arrangement and stored in six heated tanks with a total volume of 5000 cubic feet (142m^3). Between the compressors and the storage tanks, the air is dried to eliminate condensation during runs at the highest Mach number. The upper Mach number limit is due to the maximum temperature that can be achieved in the storage facility.

The test section is 1*ft* x 1*ft* x 1*ft* (0.3048*m* x 0.3048*m* x 0.3048*m*) with optical access through 1*ft* diameter windows on both sides of the test section. Models are mounted on a hydraulically controlled sting that allows for an angle of attack variation of ±10°. For flow diagnostics, a Schlieren system is used with the optical access windows on the sides of the test section. A Background Oriented Schlieren system is also currently being developed for the tunnel. In addition, static pressure ports can be used on models, for which tubing is routed to pressure transducers outside the test section through the sealed sting mechanism.

A safety shut-off valve, as well as a hydraulic feedback controlled valve that regulates the stagnation pressure during a run, are located upstream of the stilling chamber. Downstream of the test section, an adjustable second throat ensures that the start-up shock does not propagate back into the test section. Finally, the air is exhausted into the ambient atmosphere.

The performance envelope of the TWT (Figure 2) establishes the stagnation pressure limits for a given Mach number, as well as the pressure altitude (static pressure), dynamic pressure, and the Reynolds number per inch. The tunnel is currently limited at M = 4.5 and unit Reynolds numbers of approximately 1.0 X 10^6/*in* (39.4 X 10^6/*m*).

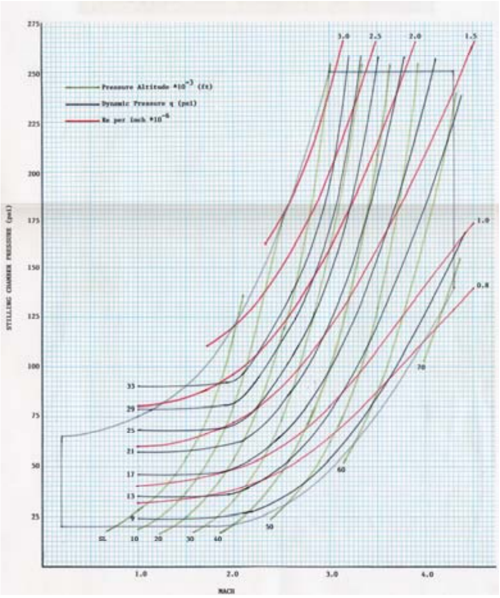

Figure 2: USAFA trisonic wind tunnel performance chart.

The TWT was originally designed as a force and moment tunnel, and it still functions well in that mode. Over the years other test requirements have led to using the TWT for a variety of tests, including: transverse jet blowing, surface pressure distributions, internal flow, and other diverse testing applications.

In addition to the research capability of the Trisonic Wind Tunnel, it has been used extensively over the years for academic purposes, especially in two courses: AE241 (Aerothermodynamics) and AE442 (Advanced Aerodynamics). AE241 introduces concepts of isentropic flow, total and static pressure and temperatures, normal and oblique shocks, and converging-diverging nozzle operation. All of these concepts are solidified in an experiment (lovingly referred to as the Viking Probe experiment), where a total pressure probe and a static pressure probe, in addition to the tunnel total and static measurements, are used to estimate the test section Mach number using a variety of methods (see Figure 3).

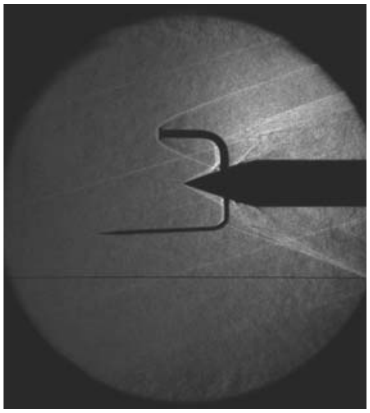

Figure 3: Schlieren photograph of total and static pressure probes in Trisonic Wind Tunnel.

In AE442 a more advanced experiment is performed in the TWT. A rectangular wing with a symmetric diamond wedge airfoil section is run at supersonic speeds in order to demonstrate three dimensional effects in high speed flow. The students measure pressure along two chord-wise rows of pressure taps, as shown in Figure 4. The pressure measurements are then compared with theoretical values as well as computed values using an Euler computational fluid dynamics prediction. The combined theoretical/experimental/computational approach to the experiment makes this project truly unique and valuable to the students, and demonstrates the richness brought to our courses by facilities such as the TWT.

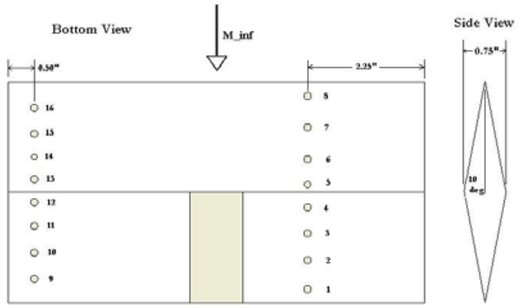

Figure 4: Rectangular wing pressure taps for Trisonic Wind Tunnel test.

3. USAFA Mach 6 Ludwieg Tube

The aerothermodynamic design of hypersonic vehicles, including reusable reentry vehicles and cruise vehicles, requires accurate knowledge of the pressures, skin friction, and thermal loads on various parts of the vehicle. These flow features can also be greatly influenced by boundary layer transition, since laminar and turbulent boundary layers have very different viscous and thermal properties. Being able to model these flows in ground-based facilities is a key issue in the future development of hypersonic vehicles. However, hypersonic ground-based facilities are traditionally very expensive to operate and maintain.

One alternative to traditional, expensive ground-based experimental facilities for hypersonic flow is the Ludwieg tube. Because of their low operational cost and good flow quality, Ludwieg tube blow-down tunnels are of special interest for hypersonic testing. Ludwieg tubes do not require a total pressure control device or large settling chamber which are common for conventional blow-down tunnels (such as the TWT at USAFA). This greatly reduces the size and cost of operating the tunnel, since large compressors, heaters, and pressure vessels are not required for their operation. The operational costs for a Ludwieg tube have been further reduced by the use of a fast-acting valve instead of the traditional bursting diaphragm that was originally part of the tunnel design in the 1950s in Germany[9].

Since no mechanisms are necessary to control pressure or temperature during the run of a Ludwieg tube, the tunnel can be described as an 'intelligent' blow down facility[8]. Here is a description of how the Ludwieg tube works, as shown in Figure 5. The test gas, which is typically air, nitrogen, or helium, is stored in a long charge tube. The charge tube is connected to the nozzle, test section, and vacuum tank via a fast-acting valve. Once the valve is opened, an unsteady expansion wave travels at the speed of sound, a_T, down the charge tube. This expansion wave accelerates the gas to a tube Mach number, Ma_T, which is determined by the area ratio of the tube and the nozzle throat. The expansion wave travels up and down the tube, which creates a constant steady flow to the expansion nozzle with pressure and temperature determined by the one-dimensional unsteady expansion process. Upon the return of the reflected wave from the end of the tube to the nozzle throat, the valve is closed and the test is finished. The length of the tube, L, and the speed of sound in the tube, a_T, determines the run time, t_R, of the tunnel[8].

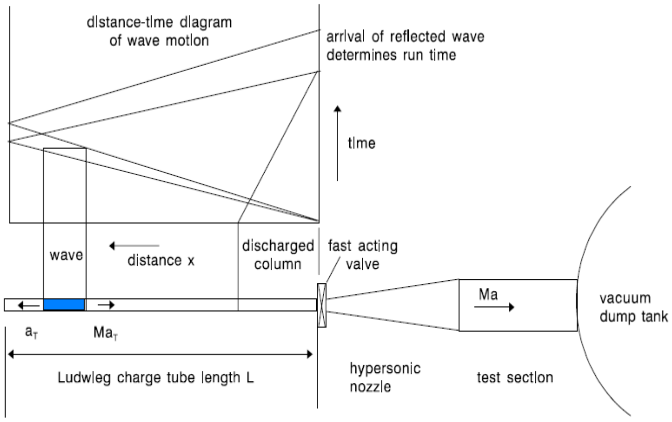

Figure 5: Hypersonic Ludwieg tube operating principle with wave diagram[8].

When compared to a standard blow-down tunnel, the Ludwieg tube provides the following advantages[7,8]:

- an extremely short start and shut off time for the tunnel
- no regulation of pressure and temperature during the run time is necessary
- extremely low mass and energy loss during the tunnel start and shut off
- due to the elimination of regulation valves, the entrance flow to the nozzle can be kept extremely clean, which results in flow with low turbulence levels
- a facility very well suited for transient heat transfer tests
- the tunnel has no “unit Reynolds number” effects like other tunnels
- from the first three advantages listed above you obtain *an extremely affordable test facility*, requiring only typical laboratory power for operation

The Mach number in the test section is determined by the nozzle and corresponding throat inserts. The stagnation pressure and stagnation temperature can be adjusted from the main control board prior to a shot. The interval between shots can be as low as four minutes (due to the relatively small volume of air in the charge tube), and the shot duration is approximately 100*ms*. The short duration of the shot is the only real disadvantage of the tunnel, requiring high-speed measurement and control equipment to make meaningful measurements of the flow field.

With the relatively simple design and low operation costs, it would be logical to assume that there would be numerous Ludwieg tubes at universities and research centers, but quite the opposite is true. As of a few years ago, only the Ludwieg tubes shown in Table 1 were known to exist or be in operation. Of these existing tunnels, only a relative few are in the United States (and none of them is owned by the DoD), meaning that affordable hypersonic ground-based testing is primarily being conducted outside the United States.

Table 1: Known Ludwieg tubes[6,8,10].

Tunnel	Location	Tunnel Description
RWG	DNW Göttingen, Germany	M = 2.9 to 6.9 0.5*m* diameter test section
Cryogenic Transonic	DNW Göttingen, Germany	M = 0.25 to 0.95 0.4*m* diameter test section
Shock-Wind Tunnel	TU Stuttgart, Germany	M = 1.76 to 4.5 0.8*m* x 1.2*m* test section
HHK	HTG, Germany	M = 6 to 11 0.25*m* diameter test section
ZARM Tunnel	University of Bremen, Germany	M = 6 to 11 0.25*m* diameter test section
HHK	TU Braunschweig, Germany	M = 6 to 11 0.50*m* diameter test section
HHK	TU Dresden, Germany	M = 6 to 11 0.25*m* diameter test section
HTFD	TU Delft, The Netherlands	M = 6 0.35*m* diameter test section
YT1 Tube	Central Aerohydrodynamic Institute, Russia	M = 5 to 10 0.50*m* diameter test section
?	Steliana Institute for Aeronautics, Romania	Operational status unknown
Ludwieg Charge Tube	Pohang University, South Korea	Quiet supersonic
Ludwieg Tube	CalTech, USA	M = 2.3 0.2*m* x 0.2*m* test section
LENS II	CUBRC, USA	M = 3 to 7 1.50*m* diameter test section
Boeing/AFOSR Quiet Tunnel	Purdue University, USA	M = 6 0.24*m* diameter test section
Ludwieg Tube	NASA Marshall, USA	M = 0.2 to 2.2 0.90*m* test section (not operational)

The basic equipment required to operate a Ludwieg tube is shown in Figure 6. The tunnel requires the charge tube (described earlier), which is a stainless steel tube of 10*m* to 50*m* in length, depending on the run time requirements of the tunnel. The charge tube is pressurized by a compressor that usually only requires typical laboratory power and which can be stored directly below the tunnel. The charge tube is separated from the nozzle, test section, and vacuum tank by a fast-acting valve. The fast-acting valve is a crucial aspect of the operation of the tunnel, since the tunnel will not create the desired conditions in the test section if the valve is not correctly manufactured. The nozzle length and shape determine the Mach number in the

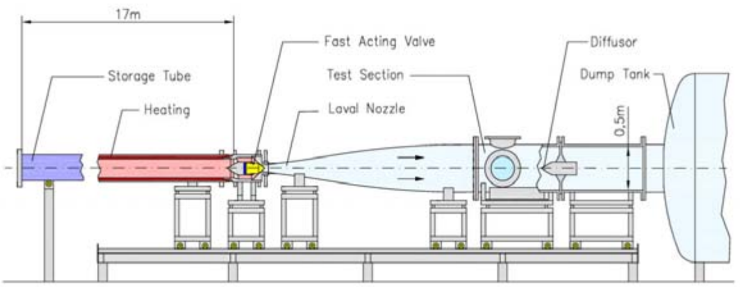

Figure 6: Ludwieg tube at Technical University of Braunschweig[7].

test section, and are also typically manufactured from stainless steel to keep the tunnel clean. The test section, including the optical access windows, is where the vehicles of interest are placed and data collected. This is immediately followed by a diffuser and the vacuum dump tank, which is typically a standard pressure vessel. The entire tunnel is a combination of typical sections that could be manufactured in most modern laboratories (the charge tube and vacuum tank) and precision manufactured sections that must meet exacting specifications in order for the tunnel to operate correctly (the valve, nozzle, and test section).

The current design for a $M = 6$ Ludwieg tube at USAFA is being completed by Hypersonic-Technology-Göttingen (HTG) in Germany. The tube will have a 0.5*m* diameter test section and a charge tube of 24*m* in length, which will produce a run time of 90*ms* and a shot time of several minutes. The charge tube will be staged (see Figure 7), with a heated section useful for heat transfer measurements. This will allow the tube to be used for both transition testing on cones and blunt bodies, as well as heat transfer testing on blunt bodies. A 5 to 6 m^3 vacuum tank will be required and will need to maintain 1 *mbar* of pressure after the run. The useful life of such a facility will be decades (as evidenced by our current TWT which was built in the 1950s).

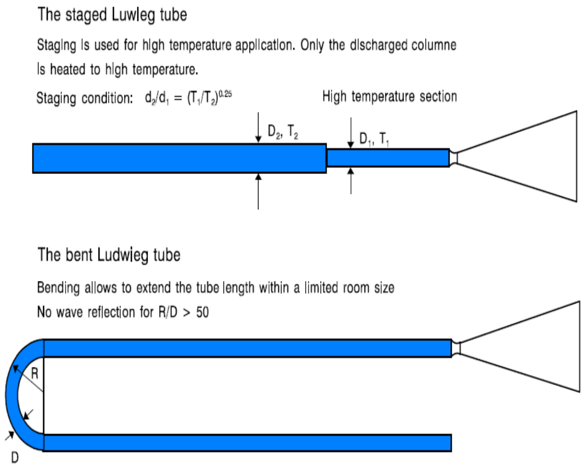

Figure 7: Staged and bent Ludwieg tubes[8].

4. Collaboration Opportunities

A Background Oriented Schlieren system is currently being developed for the tunnel, an excellent example of the type of collaborative research available with the new tunnel. A French Air Force officer visiting USAFA, and working with cadets and faculty on this project, will fulfill his master's degree project requirements. Other collaborative research possibilities include development of the thermal imaging camera system for heat transfer measurements, development of the high speed pressure measurement system, as well as the initial flow quality survey of the tunnel. Once the tunnel and instrumentation is fully developed, numerous research and educational opportunities will exist with the tunnel, as we envision this tunnel as a national resource available for collaborative research with academia and government labs.

The extensive facilities, including those described here, are primarily in place to enhance the education of the cadets at USAFA, an undergraduate-only institution. This is accomplished through a mandatory research experience in their junior or senior year. Typically, two students are paired with a faculty member or researcher in the solution of a unique, current and relevant research effort over the course of a semester. Students participate in experiment planning, conduct and reporting with their senior partner, often resulting in conference and journal publications where they are co-authors. This program of integrating research into the undergraduate curriculum has paid significant benefits in terms of student development and preparation. The partnership with a senior, experienced engineer ensures their development and mentorship, while producing quality research products for sponsoring agencies and partners.

To that end, and because there are no local graduate students to provide this mentorship, the Department of Aeronautics continually seeks collaborators through a range of programs. These include faculty on sabbatical, post-doctoral fellowships through the National Research Council, summer faculty fellowships, the Engineer and Scientist Exchange Program for employees of allied governments, graduate student internships, and occasionally, direct hires. Typically, a collaborator will bring a larger research program to the institution, and involve different student teams in the work on a semester-by-semester basis. The partner gains access to these highly capable facilities which may otherwise be cost-prohibitive, along with machine shop, technician and engineering expertise to support their experiments. USAFA and the students gain from the collaborator's experience, knowledge and mentorship. Potential partners wishing to make use of the facilities and support the development and commissioning of the Ludwieg Tube are encouraged to contact the authors through the email addresses above to discuss opportunities for collaborative research.

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