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TEST ACTIVITIES IN THE LANGLEY TRANSONIC DYNAMICS TUNNEL AND A SUMMARY OF RECENT FACILITY IMPROVEMENTS

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Abstract

The Langley Transonic Dynamics Tunnel (TDT) has provided a unique capability for aeroelastic testing for over forty years. The facility has a rich history of significant contributions to the design of many United States commercial transports, military aircraft, launch vehicles, and spacecraft. The facility has many features that contribute to its uniqueness for aeroelasticity testing, perhaps the most important feature being the use of a heavy gas test medium to achieve higher test densities compared to testing in air. Higher test medium densities substantially improve model-building requirements and therefore simplify the fabrication process for building aeroelastically scaled wind tunnel models. This paper describes TDT capabilities that make it particularly suited for aeroelasticity testing. The paper also discusses the nature of recent test activities in the TDT, including summaries of several specific tests. Finally, the paper documents recent facility improvement projects and the continuous statistical quality assessment effort for the TDT.

Introduction

The Langley Transonic Dynamics Tunnel (TDT) was developed in response to a request in the early 1950's by NACA[1] personnel to develop a transonic wind tunnel facility dedicated to aeroelasticity research and flight vehicle flutter-clearance activities. Reference 1 lists the following requirements that were originally stated for the desired facility: 1) that the facility be as large as feasible to enable accurate simulation of model details, such as control surfaces; 2) that the facility be capable of operating over a wide range of density in order to simulate various altitude conditions, because flutter characteristics often change with altitude; 3) that the facility use Freon gas as the test medium which, based on previous experience, enables the use of heavier, less expensive models, results in higher Reynolds number, and allows more efficient power usage; and 4) that the facility be capable of operating at Mach numbers up to 1.2. The NACA's answer to this request for a new facility was the conversion of the Langley 19-ft Pressure Tunnel to the TDT. The new wind tunnel would have all the features originally requested: a 16-by-16 ft test section that could operate at Mach numbers up to 1.2 with variable pressure conditions in either air or a heavy gas with the chemical name dichlorodifluoromethane and hereinafter referred to as R-12. The design and conversion process began in 1954 and the TDT became operational in early 1960.[2] At the time, the TDT represented a significant advancement in aeroelastic testing capabilities, primarily because of its large size, heavy gas test medium, and transonic speed capabilities. Figure 1 shows an aerial view of the current TDT. Reference 3 is a history of the facility that discusses most major changes and improvements to the TDT since it began operations.

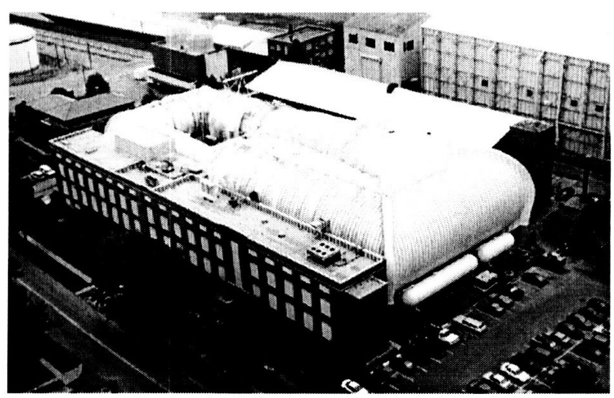

Fig. 1- Aerial photograph of the TDT.

Over the decades, the TDT has served as a workhorse for experimental aeroelastic research and vehicle flutter-clearance testing. Testing has included such varied

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[1]National Advisory Committee for Aeronautics, the predecessor organization for the National Aeronautics and Space Administration (NASA).

aeroelasticity concerns as buffet, divergence, gusts loads, flutter, and other types of dynamic response. In addition to testing for these phenomena, many passive and active control studies have been carried out in the TDT to demonstrate methods of overcoming aeroelastic obstacles to flight. References 4-11 provide overviews of testing that has occurred in the TDT over the years. Most military fighters and commercial transports developed in the United States that are capable of flight at transonic speeds have been tested in the TDT at some time in their development history. Today, the TDT is still a unique facility with respect to its heavy gas testing and other capabilities; however, it has undergone many changes over the years in order to remain the world's premier transonic aeroelastic testing facility.

This paper will discuss key features of the TDT that make it particularly well suited for conducting aeroelasticity tests. A discussion of recent test activities will then ensue that will lead to an examination of factors that may be contributing to recent changes in the types of tests conducted in the TDT. Several recent tests will also be specifically discussed briefly. The paper will conclude with discussions of a number of facility improvements that have been implemented within approximately the last five years.

The Langley Transonic Dynamics Tunnel

The Langley Transonic Dynamics Tunnel (TDT) is a large wind tunnel built for the purposes of conducting aeroelastic research and of clearing vehicles of aeroelastic phenomena such as flutter. The TDT is capable of achieving a Mach number of 1.2 in both air and heavy gas test mediums. The TDT has a variable pressure capability from near vacuum to about one atmosphere. The 16 x 16 ft test section allows the testing of reasonably large models. The high density available by using the heavy gas capability (compared to air) provides a great advantage in the scaling of aeroelastic models. It is this combination of large test section size (allowing large model scale), high speed, high density, and variable pressure that makes the TDT ideally suited for testing aeroelastically scaled models. In addition to these facility-operating characteristics, there are a number of other facility features that help make the TDT particularly suitable for aeroelasticity testing. Figures 2 and 3 show a plan view and a test section area cross-sectional view of the TDT.

Aeroelastic testing capabilities

Test Medium- Testing can be conducted in the TDT using either air or a heavy gas as the test medium. Prior to 1997, the TDT used R-12 for the heavy gas test medium. Environmental constraints on the use of R-12 were being accelerated at the end of the 1980's to the point that its future availability for wind tunnel testing was at risk and its cost was rising rapidly. An effort was initiated at NASA Langley to identify a new candidate heavy gas. The gas chosen to replace R-12 in the TDT was 1,1,1,2-Tetrafluoroethane (CH_2FCF_3), also identified as R-134a. Some of the principle properties of R-134a, R-12, and air are shown in Table 1. The operating boundaries of the TDT in air and R-134a are shown in Figure 4.

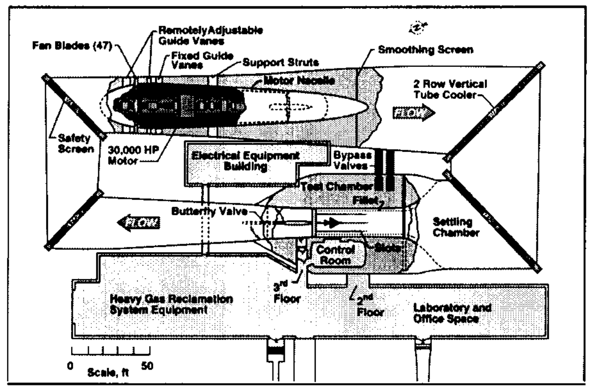


Fig. 2- Plan view drawing of the TDT facility.

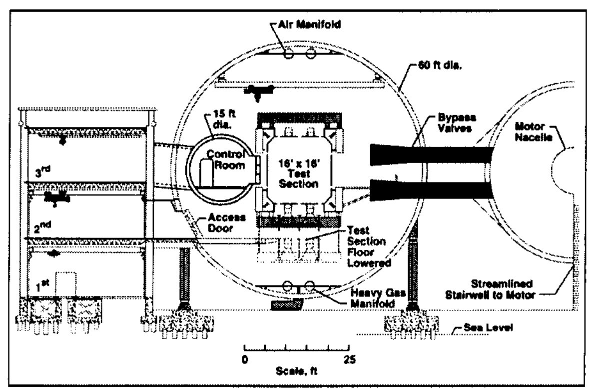


Fig. 3- Cross-sectional view of the TDT test section area.

Testing in a heavy gas provides aeroelastic model scaling advantages. The density of R-134a is approximately 3.5 times that of air. This means that aeroelastically scaled models can be made heavier relative to a similarly scaled model for testing in air. This relatively heavier model generally makes the task of building the model with sufficient strength easier. Also, the time (or frequency) scaling allows models to be designed with natural frequencies that are approximately half the value that would be required to provide a scaled model for testing in air. This decrease in required model frequencies means simulated vehicle instabilities will occur at lower frequencies during wind tunnel testing. Slower developing instabilities generally makes wind tunnel testing in the heavy gas safer when compared to testing of scaled models for the air test medium.

Table 1: Some properties of R-134a, R-12, and air.

	Test medium		
Property	R-134a	R-12	Air
Molecular weight	102.03	121.00	28.97
Ratio of specific heats, γ	1.13	1.14	1.40
Speed of sound, ft/sec	540	505	1116

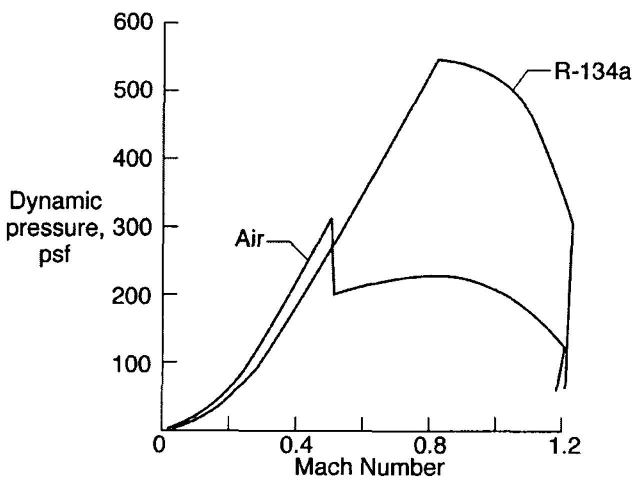


Fig. 4: TDT Air and R-134a operating boundaries.

Bypass Valves- A unique safety feature of the TDT is a group of four bypass valves connecting the test chamber (plenum) of the tunnel to the portion of the wind tunnel circuit just downstream of the drive motor (see Fig. 3). When these valves are opened, some of the relatively high-pressure test medium downstream of the tunnel drive fan flows through the valve tubes into the lower-pressure test chamber. This causes a change in the tunnel test section mass flow and pressure, resulting in a rapid reduction in the Mach number and dynamic pressure in the test section. In the event of a model instability, such as wing flutter, these quick-actuating bypass valves can be opened in an attempt to save the wind tunnel model from a catastrophic failure.

Test Section Isolation System- The test section and test chamber plenum area of the TDT can be isolated from the remainder of the tunnel circuit by a butterfly valve and a gate valve (see Fig. 3). This isolation allows access to the wind tunnel model with the convenience of leaving the R-134a heavy gas in the remainder of the wind tunnel circuit, even under low pressure. This feature significantly reduces gas-processing time and, therefore, greatly increases the test efficiency of the facility.

Research Laboratory Areas- An important aspect of aeroelastic testing is the preparatory work that takes place prior to conducting a wind tunnel test. In addition to standard instrumentation calibrations and model geometry measurements that would be typical of most wind tunnel models, aeroelastic models often undergo ground vibration testing, stiffness measurements, elastic axis determination, end-to-end/performance tests of active controls systems, inertia property measurements, and other miscellaneous tests. The TDT facility currently provides several distinct laboratory areas for the preparation of models.

In a building connected to the TDT, known as Building 648, there is a model preparation area that is generally used for the preparation of fixed-wing models. This laboratory has a strongback for mounting sidewall- or sting-mounted models. Three faces of this strongback can potentially support sidewall-mounted models and one of these three faces is most suitable for supporting sting-mounted models. A valuable capability of this model preparation area is the ability to directly communicate with the computer data acquisition system used for TDT wind tunnel testing. This capability allows instrumentation calibration, model ground testing, and computer system setup with some of the actual computer hardware that will later be used for the wind tunnel test. A second fixed-wing model preparation area has recently been constructed for use in preparing TDT models for testing. This new area is discussed in greater detail later in this paper as a facility improvement.

In a building adjacent to the TDT, known as Building 647, there are two areas demarcated for helicopter model preparation. The Aeroelastic Rotor Experimental System (ARES) floor-mounted testbed uses one of these test areas. The second test area was added in the early 1990's and has been dedicated to the preparation of tilt-rotor models. Cages made of steel surround both areas to encompass the rotor systems to a height approximately one–rotor diameter above the model rotor plane. The cage is intended to capture any rotor blade debris in the event of a failure during hover testing.

Model Mount Systems

Sidewall Mounts- Over its history, several different sidewall-mount model support systems have been available at the TDT for use in testing semispan models. The primary sidewall system has always consisted of an electrical motor driven turntable plate to which the wind tunnel model is mounted. Sidewall mount systems provide the capability of testing half models from which the aeroelastic behavior of full-span vehicles can be inferred.

A requirement for a semi-span model mount system that could oscillate in pitch at reasonably high frequencies led to the latest sidewall-mount system. This new system is known as the Oscillating Turntable, or OTT. The OTT became operational in 2000. An example of a semispan model mounted on the OTT is shown in Figure 5. Since this is a relatively new facility capability, the OTT will be discussed in more detail later in the paper.

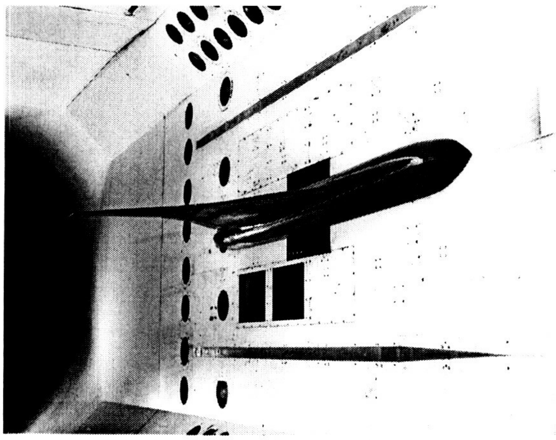


Fig. 5- A NASA High Speed Research program model mounted to the OTT sidewall support system.

Sting support- Another class of support systems at the TDT is a movable sting. Sting-mounted models are usually full span, so they generally provide a more representative aeroelastically scaled wind tunnel model, as fuselage carry-through structure and total vehicle inertial and aerodynamic properties can be modeled more accurately than with semi-span models. The TDT sting support system is capable of traversing vertically in the test section. The sting support can also rotate in pitch through a range of approximately ±15°. A sting-mounted model is shown mounted in the TDT in Figure 6.

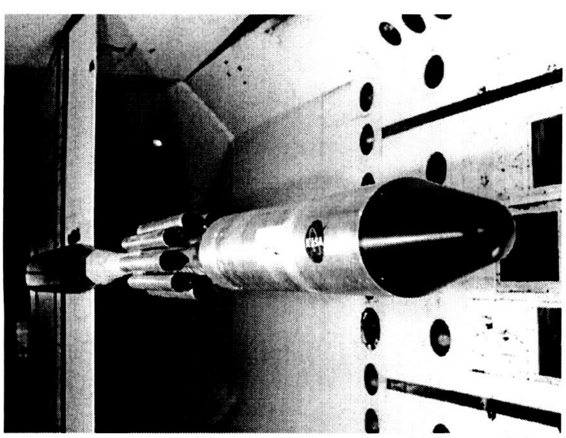


Fig. 6- Photograph of Delta III launch vehicle model sting-mounted in the TDT.

Cable mount- Perhaps the model mount system most compatible with aeroelastically scaled model testing is the TDT cable-mount system. The cable-mount system at the TDT consists of two cables that support a full-span model in the test section through pulleys mounted in the model. The cables are sized according to model load requirements to minimize their interference with model structural, inertial, and aerodynamic properties. Springs are mounted in one of the cables to provide cushioning in the support system so that the flight stability modes of the cable-supported model will simulate the actual vehicle flight stability modes reasonably well. A photograph of a cable-mounted model is shown in Figure 7. Reference 12 summarizes many of the system parameters that were considered in designing a modern fighter-aircraft model to be tested on the TDT cable-mount system.

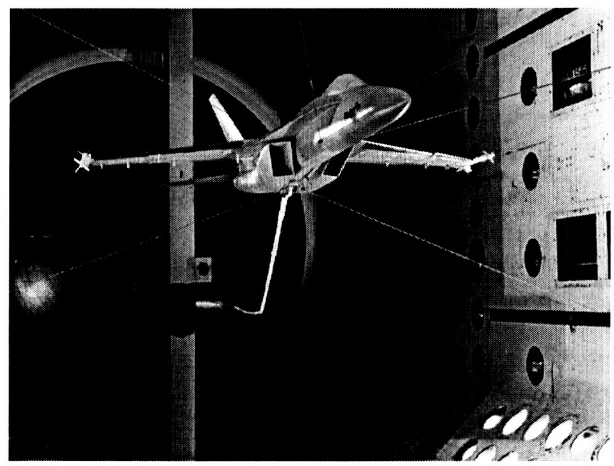


Fig. 7- F/A-18 E/F model cable-mounted in the TDT.

Floor mounts- Several floor-mount configurations have been used at the TDT. Floor mounts are primarily used because they either simulate the physical situation better, such as ground proximity in the case of a launch vehicle on the launch pad, or because this type of support provides a simpler arrangement from which to carry large loads and large models. Two of the most extensively used floor-mount systems are shown in Figures 8 and 9.

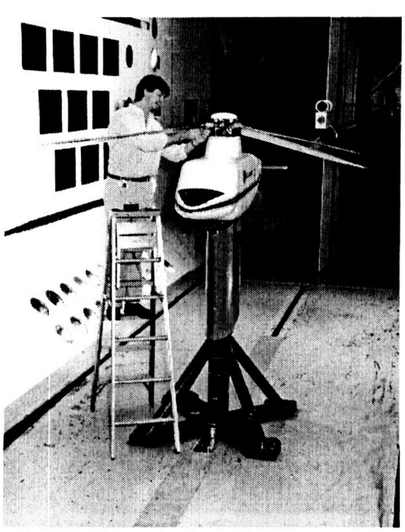


Fig. 8- ARES testbed on floor mount stand.

Figure 8 shows a fixed mount system that supports the ARES testbed. This stand and helicopter model testbed has been used for many research studies of aeroelastically scaled rotor blade systems. Figure 9 shows a launch vehicle model mounted on a floor turntable system. This mount system is intended for low-speed testing of ground-mounted models. Reference 9 provides a summary of the ground wind loads tests that have taken place in the TDT, many of which used the floor-mount turntable.

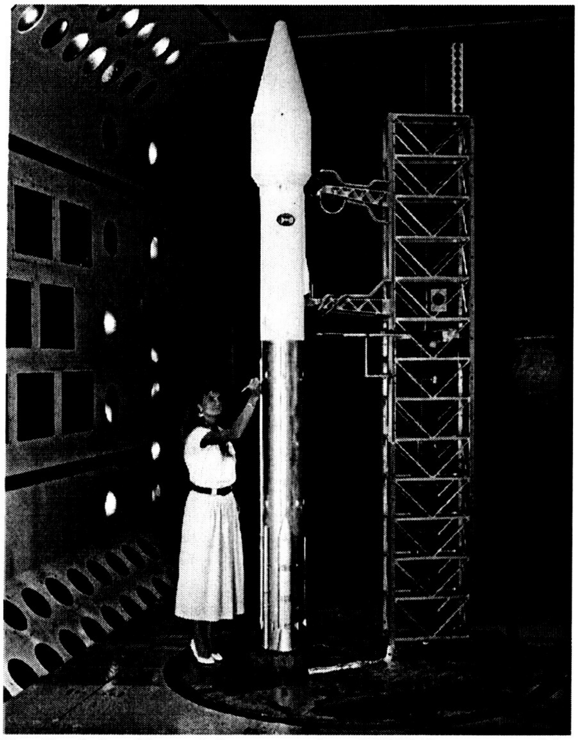


Fig. 9- Atlas II model mounted on TDT floor turntable.

Recent Test Activities

The following four paragraphs present specific examples of recent non aeroelastic tests in the TDT. Examples of aeroelasticity-related TDT tests are covered in separate papers that were presented as part of the special session on aeroelastic wind-tunnel testing at the 2003 AIAA Dynamics Specialist Conference. These test reports are available as references 13-16.

MER Parachute

In support of the Mars Exploration Rover (MER) mission, a series of parachute models were tested in the TDT. The TDT was chosen for testing these parachute models for two main reasons: 1) the very low-pressure conditions that the TDT can reach, and 2) the relatively large test section size. The main objective of this test was to obtain quantitative drag and stability data of candidate parachutes, and of the re-entry backshell. The test matrix concentrated on conditions that best simulated the terminal descent conditions in the Martian atmosphere. A sidewall-mounted truss was constructed to support the parachute models behind a backshell model placed to simulate aerodynamic blockage effects of the payload backshell. The truss arrangement supported the parachute from a balance located at the apex of the canopy suspension lines. This balance provided for the measurement of parachute drag during zero angle of attack testing. A photograph of one of the parachute models in the single-balance test configuration is shown in Figure 10. To measure load and stability data at angle-of-attack conditions, a rod was passed through a slide attachment fitted to the center of the parachute canopy. A balance supporting this rod was itself mounted to the downstream portion of the sidewall truss model support system. The combination of the forward and aft constraints allowed for the parachute to be positioned and tested at angle of attack. The combination of the forward balance at the apex of the suspension lines and the aft balance measuring side loads at the parachute canopy vent allowed the measurement of tangential and normal forces on the parachute at angle of attack. A photograph from downstream of the dual-balance configuration is shown in Figure 11. A total of five parachute configurations were tested. The results from this test will be used to support parachute system design decisions for the MER mission.

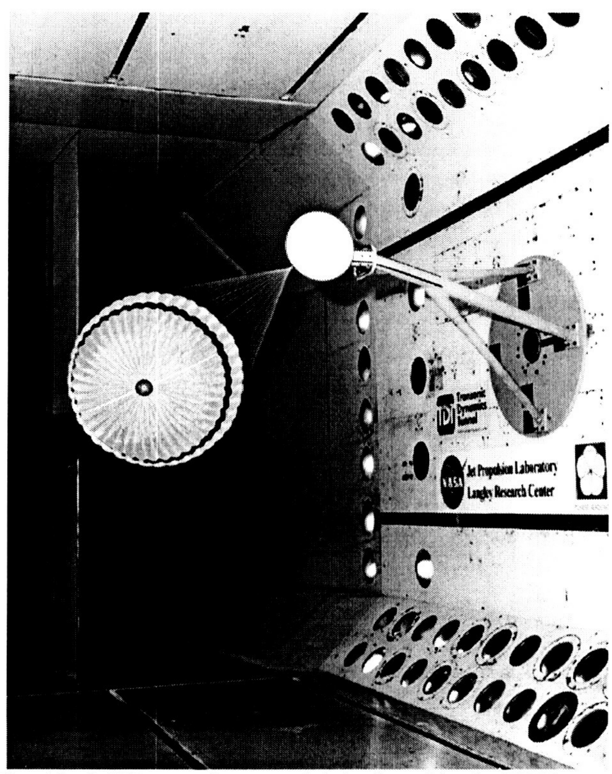


Fig. 10- MER parachute model deployed in the TDT during low-velocity testing.

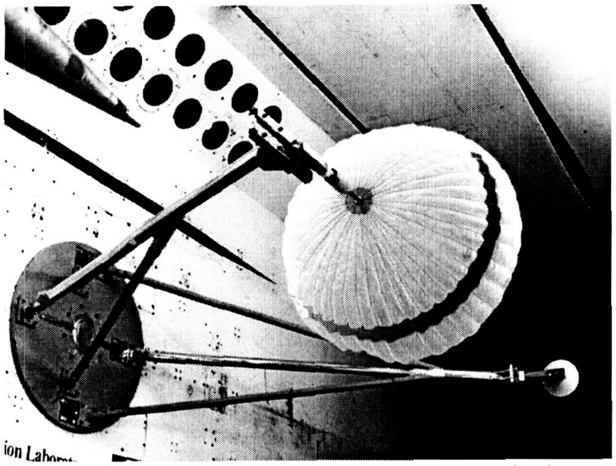


Fig. 11- Photograph of a MER parachute model in the dual-balance configuration from downstream.

Mars Scout Vehicle

In recent years, there have been several aerodynamics tests conducted in the TDT for flight vehicle concepts that could be flown in the atmosphere of Mars. The most recent example of such a concept was associated with the Mars Scout program. The vehicle concept for the Mars Scout was a folding wing configuration. The folding wing allows for a smaller volume payload package for spacecraft transportation to Mars, as well as minimizes the size of the reentry shield needed to survive entry into the Mars atmosphere. The TDT was chosen for this test because of the very low pressure conditions that the TDT can reach, even at transonic Mach number conditions. These conditions allow key aerodynamic properties, such as Reynolds number, to be realistically matched with Mars atmospheric conditions expected at the altitude of wing deployment. The TDT test was used to demonstrate a mechanical concept for deploying the wings, with the goal of demonstrating repeatable deployment over a range of model attitude and flight conditions. A photograph of the sting-mounted model in the TDT during the last stages of wing deployment is shown in Figure 12. A photograph of the model in the fully deployed configuration in the TDT test section is shown in Figure 13.

Free-To-Roll Testing

A new type of test conducted in the TDT in 2001 demonstrated a transonic free-to-roll capability for the purpose of screening vehicles in an attempt to predict flight lateral stability problems such as wing rock/wing drop via a sting-mounted model. The first test of such a model in the TDT was the F/A-18E configuration shown in Figure 14. This test resulted in the first conclusively demonstrated wing drop event on an F/A-18E in a wind tunnel setting. It also provided the technical evidence necessary to justify developing a new free-to-roll rig that can be used for testing conventional performance wind tunnel models in transonic wind tunnels.

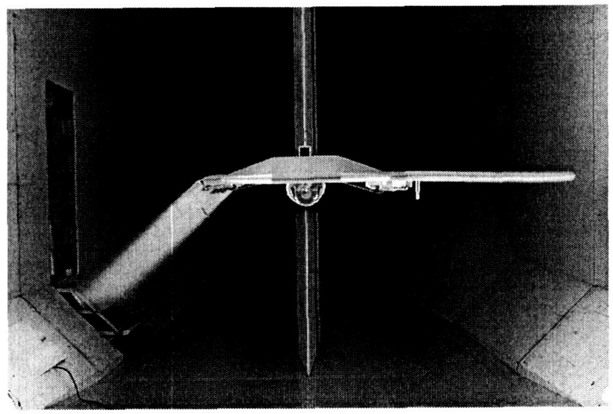


Fig. 12- Mars Scout in TDT viewed from upstream with right wing in transition to full deployment.

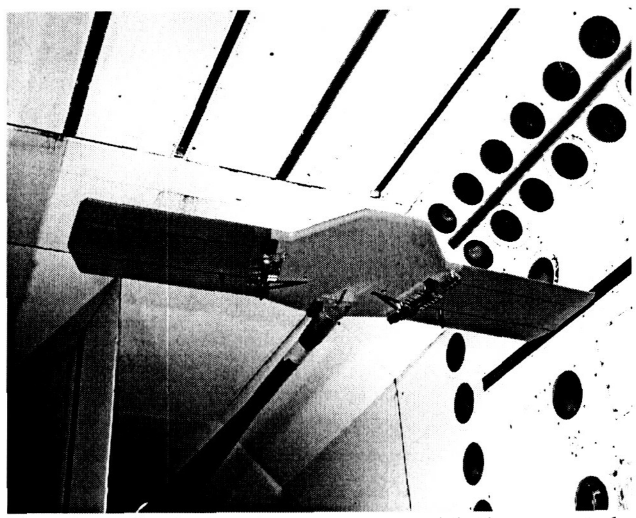


Fig. 13- Fully deployed Mars Scout model sting mounted in the TDT test section.

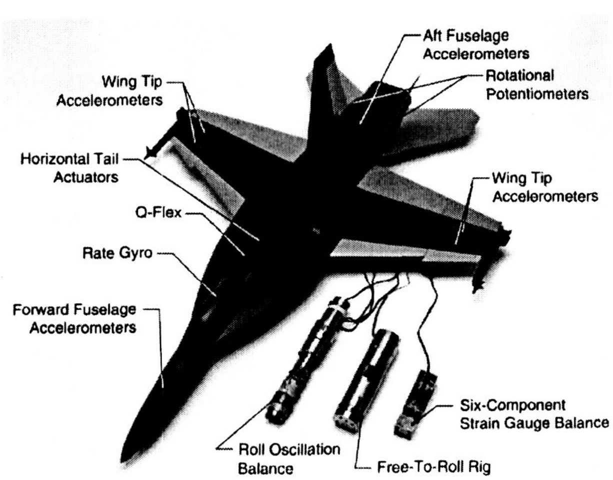


Fig. 14- F/A-18E Free-To-Roll model with various mounting/load-measurement mechanisms.

Circulation Control Airfoil

A basic research study was recently conducted in the TDT of a circulation control airfoil that takes advantage of the Coanda aerodynamic effect at the trailing edge of the wing. The model was a semispan, straight wing configuration that was sidewall mounted to a large splitter plate in the TDT test section. A photograph of the wing model is shown in Figure 15. Slots were built into the wing to allow forced air to be blown out onto the trailing edge region of the model The Coanda trailing edge shape and the wing internal plenum shape are shown for one model configuration, with the wing tip of the model removed, in Figure 16. Such blowing modifies the loads generated by the wing as a result of the jet interacting with the freestream flow and the trailing edge via the Coanda effect. Configuration parameters that were varied

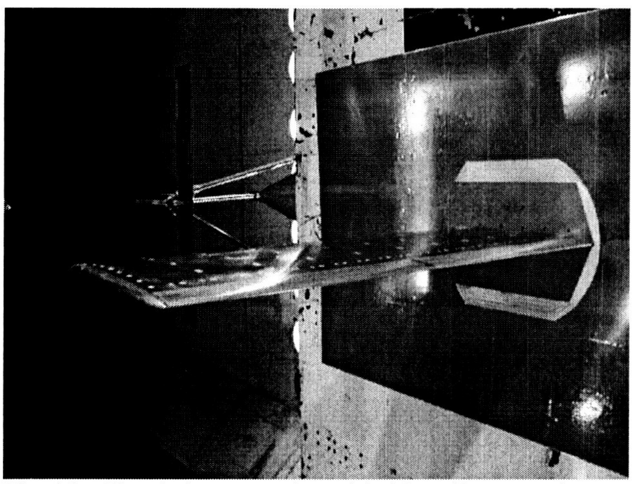


Fig. 15- Circulation control model sidewall mounted to a splitter plate in the TDT with a wake-measuring rake mounted downstream of the model.

via model hardware changes during the test were the trailing edge Coanda shape and the slot height. Three Coanda shapes and four slot heights were tested. Model measurements for this test included internal plenum total pressures and temperatures and surface static pressures. In addition to the three-dimensional configuration shown in Figure 15, the model was also tested with a circular plate attached at the wing tip to provide a simulated two-dimensional flow so that fundamental properties of the circulation control effects could be assessed independent of three-dimensional aerodynamic effects. A wake rake was also included in the test apparatus, mounted near the trailing edge of the wind tunnel splitter plate (visible in Figure 15). Total and static pressures were measured using the wake rake. By integrating the available flow-field pressures, lift, drag, and pitching moments could be estimated for the model. These forces and moments can then be integrated to calculate the effects, the effectiveness, and the augmentation ratios obtained from the blowing on the trailing edge Coanda surfaces. This test was different from most previous Coanda circulation control studies in that it emphasized aerodynamic measurements at transonic flight conditions, and on an airfoil shape much thinner than most circulation control studies used in the past. The airfoil used in this study could be considered representative of a modern fighter aircraft shape in terms of thickness. A second TDT entry of this model is planned for October 2003.

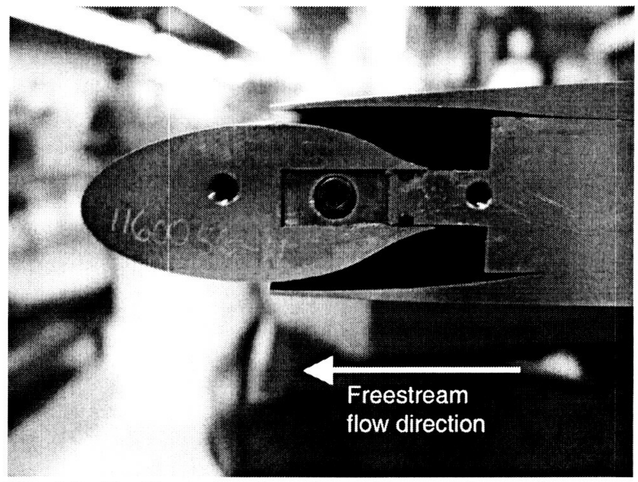


Fig. 16- Trailing edge Coanda surface and internal plenum chamber of wing (wing tip removed).

Facility Improvements

The TDT is anticipated to continue to provide a unique capability for testing aeroelastic and non-aeroelastic model systems well into the foreseeable future. Several specific facility improvement projects have been completed in recent years with the goal of sustaining and improving the test capabilities of the TDT. This section discusses these completed projects, as well as one ongoing project and one continuous assessment project. As a whole, these projects are aimed at improvements in wind tunnel data quality, testing productivity, and model preparation capabilities.

R-12 to R-134a Conversion- Replacing the primary test medium for the TDT, as discussed earlier in this paper, required a number of facility modifications. Conversion work began in 1990 with the original conventional refrigerant refrigeration system used to chill the gas/air mixture during heavy gas reclamation operations being replaced with two cryogenic condensers that operate in series. Similar to the old refrigeration system, the new condensers reduce the temperature of the gas/air mixture so that more of the gas would condense out of the mixture for storage and re-use. The new condenser units use liquid nitrogen to obtain temperatures in the vicinity of −200°F. Until 1996, these condenser units were used for processing the original R-12 heavy gas. After the full conversion to R-134a in 1997, the cryogenic condensers continued to perform their function in recovering the R-134a. However, R-134a has a freezing point of −154°F. Therefore, the cryogenic condensers are no longer required to operate to their minimum temperature capabilities.

The TDT ceased operations for a period of approximately 18 months to complete the conversion process to the new operating gas, R-134a. The major tasks associated with the conversion were the replacement of six screw-type vacuum blowers and the overhaul of a five-stage compressor. Photographs of these two major components of the TDT heavy gas reclamation system (HGRS) are shown in Figures 17 and 18. Other changes included replacement of oil coalescing filters to keep oil in the processing equipment from migrating into the test medium and preparation of the storage tank for the new operating gas. The first research test in the R-134a test medium was conducted in June 1998. Reference 17 specifically documents the TDT heavy gas conversion project.

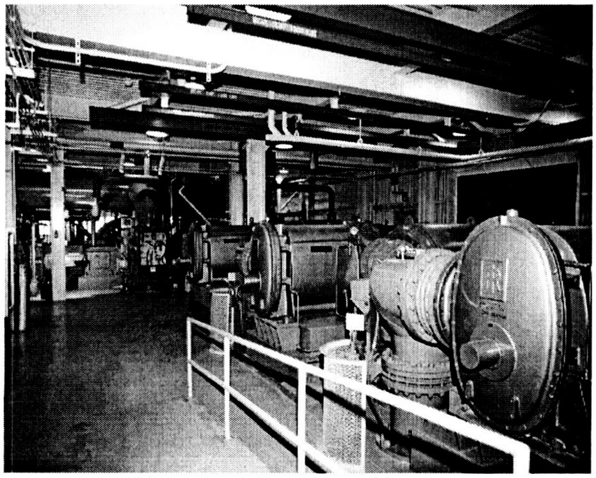


Fig. 17- TDT vacuum blowers.

Field Air Source- Until recently, air was supplied to the TDT circuit from the atmosphere after passing through a desiccant air dryer to reduce the dew point of the air being added to the tunnel. With the heavy gas conversion project, the ability to use dry, compressed air available from the air storage bottle fields at NASA Langley was added to the TDT operating capabilities. This has provided a dry air source with higher flow capacity and lower dew points than previously available with the TDT air dryers. The higher flow capacity of the new air source has significantly reduced the time required to increase tunnel pressure during air-medium testing or for tunnel entries to access the wind tunnel model during heavy gas testing. The lower dew point provides an improved test medium with regard to aerodynamic properties when conducting research testing in air and it reduces the possibility of R-134a hydrates existing, freezing during reclamation, and blocking flow in the cryogenic condensers.

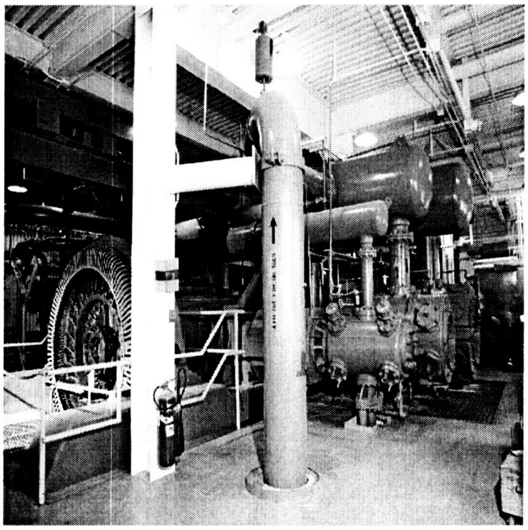


Fig. 18- Refurbished TDT five-stage compressor.

Heavy Gas Reclamation System Controls- One of the major improvements made to the facility from an operations perspective was the replacement of the original HGRS controls during the 1997 heavy gas conversion project. The original HGRS control system was limited in its ability to control system variables such as valve positions, monitor process variables such as temperature and pressure, and required the operators to make many routine decisions depending on the operating conditions. The entire control system was overhauled and the control room refurbished. New programmable logic controllers (PLC's) were installed with new graphical operator interfaces. All operator controls were moved from the original graphics panel to a dedicated console and a new graphics panel was installed which displays all critical process variables (Figure 19). A new process data acquisition system (PDAS) was installed which continuously records process variables to assess system performance and perform diagnostics. A few additional modifications were made to the HGRS controls as part of the HGRS productivity improvements project discussed in the following section.

HGRS Productivity Improvements- Lessons learned, primarily as a result of the heavy gas conversion project, led to another facility project to improve operations of the heavy gas system. These modifications resulted in simplification of some system operations and direct time savings during several operational procedures. Two of the more significant impacts are: 1) start-up time at the beginning of heavy gas operations for a given test is reduced by as much as four hours; and 2) reduced likelihood of heavy gas hydrates forming in the cryogenic condensers associated with the HGRS. In past operations, the formation of such hydrates has often led to lengthy test delays (sometimes 3-4 days) while the encapsulated cryogenic condensers were allowed to warm up to melt the hydrates internal to the system. These facility improvements were completed in February 2002.

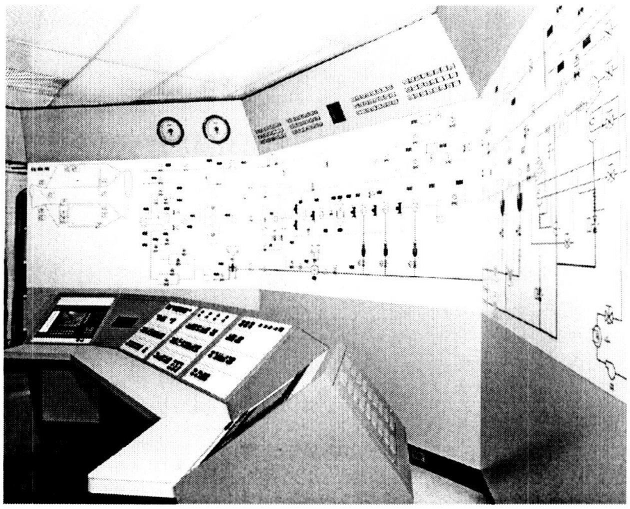


Fig. 19- Heavy gas control room as modified for R-134a.

To better understand the improvements that were implemented, a general description of the HGRS operation is provided. The HGRS is used to fill the tunnel with R-134a, regulate pressure (air and R-134a modes) between atmosphere and near vacuum (8 psf), monitor and regulate R-134a concentrations, and remove R-134a from the tunnel. The major components of the HGRS include a steam-heated vaporizer, six vacuum blowers, a five-stage 8500-ft^3/min compressor, a liquid storage tank, and two cryogenic condensers. Auxiliary systems of air, cryogenic nitrogen, vacuum, cooling water, and lubricating oil support the HGRS operation with numerous valves, instruments and extensive piping systems. When operating the tunnel in the air mode, the R-134a is stored as a liquid in the Liquid Storage Tank (LST). To fill the tunnel with the R-134a test medium, the steam-heated vaporizer is used to convert the liquid R-134a to a gas. Control valves regulate the flow rate and pressurization of the tunnel.

To remove the R-134a from the TDT, the blowers and five-stage compressor remove the R-134a from the bottom of tunnel while air is added at the top of the tunnel. Most of the R-134a gas is converted to liquid state in the last three stages of the 8500-ft^3/min compressor. The remainder of the R-134a gas is reclaimed in the two cryogenic condensers. The condensers use pressure and cryogenic cooling to convert the R-134a gas to liquid state that is sent to the LST. The HGRS is equipped with a variety of valves, either manually or automatically operated, that are used to control the R-134a gas and liquid processing. The HGRS programmable logic controller (PLC) uses inputs from valves, pressure transmitters, temperature transmitters, and gas particle count sensors to monitor and control the process. The HGRS operations are performed by automated and manual operations that are controlled by the facility technicians.

The project consisted of seven elements, four of which are summarized below. Each improvement in this project contributes to more productive aeroelastic testing and potential cost savings to facility users through reduced occupancy times required.

Stabilized compressor and condenser flow: A new 700-psig regulated air supply was added to supply the cryogenic condensers during the cool down operation prior to processing R-134a. This new automated process for purging, drying, and cool-down of the cryogenic condensers replaced a two-step static and dynamic flow process which had poor control and required operation of the 8500-ft^3/min compressor. The time required to lower the two condensers temperatures to -50°F and -150°F has been reduced by about one hour with improved temperature gradient control. The improved cool down operation significantly reduces the likelihood of R-134a hydrates forming in the condensers, which had previously resulted in lengthy test delays. A second controlled air supply was installed between stages three and four of the 8500-ft^3/min compressor. An automated pressure control valve maintains a minimum pressure at the third stage discharge and provides makeup air flow as output of the third stage drops during certain periods of the heavy gas reclamation process. The makeup air avoids compressor upper-stage pressure drops and flow disturbances that previously occurred. A new air heater was necessary to overcome the temperature drop in reducing from the 2400 psig field-air source to the new 700 psig air supply. A photograph of the new heater and associated piping is shown in Fig. 20.

Simultaneous operation of HGRS and tunnel- Valves and controls were added to allow some HGRS operations during tunnel operations and during personnel entry into the tunnel test section and plenum for model changes. The major time savings occur in preparation for tunnel operations with R-134a test medium. The cool down operation for the cryogenic condensers (~1 hour) can now be performed simultaneously with plenum entry, tunnel operations, and blower operation. Compressor and blower purging and drying operations in preparation for R-134a processing can also be performed simultaneously with plenum entry or tunnel operations This saves an additional one to two hours. Test personnel can now enter the test section during HGRS operations, even during main tunnel circuit gas-exchange operations to change the tunnel pressure or to purify the R-134a remaining in the tunnel circuit. In this scenario, the primary personnel protection devices are the TDT test section isolation valves previously discussed in this paper. By allowing parallel activities, delays in preparations for and operations with heavy gas are reduced which increases research test time and efficiency.

Fig. 20- Air heater for the new 700 psig regulated air supply associated with the HGRS.

Additionally, a 30-inch valve was added between the six vacuum blowers and the five-stage compressor as part of this project. This separation of the blowers and the compressor allows operation of the wind tunnel (air test medium only) in the event of a failure, or maintenance repair, of the compressor. With the use of the vacuum blowers, the facility can still test with air test medium pressures down to less than half of an atmosphere. This new isolation valve is shown in Figure 21.

Integrated tunnel and plenum lockout systems- For simultaneous tunnel and plenum entry during HGRS operations, modifications were required to ensure safe conditions for personnel and equipment. Several valves were installed to provide double isolations between the tunnel/plenum and HGRS equipment. The new valves as well as some existing valves were equipped with mechanical locking devices to lock the valve in the closed position. Limit switches on the valves and locking devices are interlocked through the HGRS programmable logic controller (PLC) to provide redundancies and ensure safety for personnel entry into the tunnel. The new actuators and locking mechanisms for two of the modified valves are shown in Figure 22.

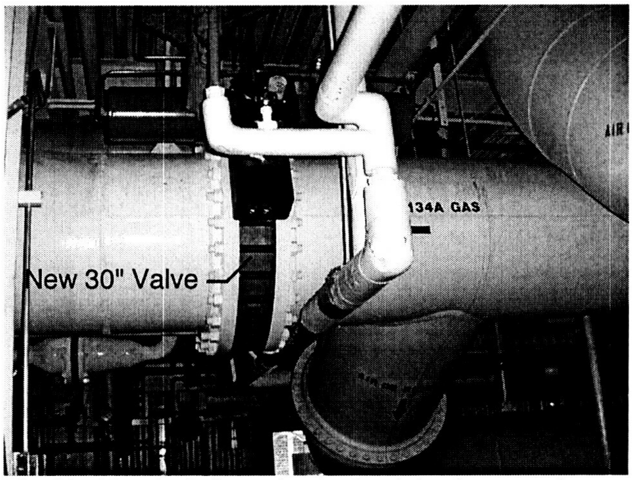


Fig. 21- New isolation valve in the piping between the vacuum blowers and the five-stage compressor.

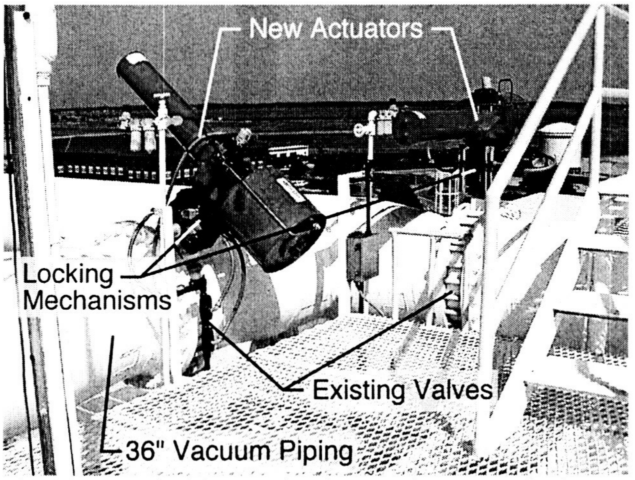


Fig. 22- New locking mechanisms and actuators for key safety valves used by the HGRS.

Vaporizer improvement- During prior operations with the vaporizer at high output rates, some of the liquid R-134a would not boil off and would enter the piping downstream of the vaporizer. This liquid served as an oil transporting mechanism causing the downstream oil separator to become overloaded, and then pass equipment oil into the piping and towards the tunnel. To avoid this situation, a cryogenic pump with oil separator level controls was installed to return the excess liquid R-134a upstream of the vaporizer. A side benefit of this modification is that the output of the vaporizer can be slightly increased. With increased vaporizer output, the time required to fill the tunnel with R-134a, which takes about one hour, can be reduced by approximately 15 minutes.

Automated Controls- Another NASA facility project is currently underway to automate control of several systems associated with operations of the TDT. Of primary concern is the ability to automatically control

Mach number of the flow via speed control of the fan-blade drive motor for the TDT. In addition to fan-blade speed control, automated control of fan-blade pre-rotation vanes and test section re-entry flaps will also be provided to further automate changing wind tunnel test conditions. Finally, improvements will be made in the control and setting of the sting-support apparatus and the sidewall, electric-motor-driven, semispan-model support system. All of these automations are aimed at conducting more productive wind tunnel tests. This will be particularly valuable for testing of non-aeroelastic models where safety risks are lower. On the other hand, fully manual operational control modes will be retained in case this is considered to be the safer manner of conducting aeroelastic tests in which slowly changing conditions are critical.

Oscillating Turntable (OTT) Apparatus- The OTT is a newly acquired research tool at the TDT that has been designed to oscillate large, semispan models in pitch at high frequencies and transonic conditions. Models may be oscillated sinusoidally at constant or varying frequencies, be subjected to a step input, or undergo user-defined motion. The OTT target oscillatory design points are listed in Table 2, of which, design point 1 is the most challenging. Table 3 lists the OTT load limits at the tunnel wall. These loads are large enough to accommodate a wide range of model sizes and test conditions.

Table 2: Performance design points for OTT.

Design point	Pitch inertia, lb_m-in^2	Frequency, Hz	Maximum angle of angle, deg
1	65,000	40	1
2	250,000	20	1

Table 3: Maximum steady OTT loads at tunnel wall.

Load	Maximum value
Lift	2,400 lb_f
Pitching moment	32,000 in-lb_f
Rolling moment	108,000 in-lb_f
Yawing moment	5,100 in-lb_f

Figure 23 highlights key components of the OTT. The OTT utilizes a powerful rotary hydraulic actuator, rated for 495,000 in-lb_f, and a digital Proportional, Integral, Derivative, Feedforward (PIDF) control system to position and oscillate models. Power for the OTT is supplied by a 3000 psi, 150 gpm hydraulic power unit that is located outside the tunnel pressure shell. Rails allow for precise positioning of the system with respect to the tunnel wall to accommodate a wide range of models and model support systems. Cam wheels and clamps lock the OTT onto its rails once it is in position to prevent the OTT from lifting off the rails during high-power oscillations. For model instrumentation, a 2.5 inch diameter hole passes through the center of the entire OTT shaft and actuator to minimize the exposure of this wiring to oscillatory motions.

The OTT also possesses a fast reacting fail-safe braking system to protect a model from excessive aerodynamic forces such as could potentially develop from uncommanded motion resulting from power or OTT system failures. Figure 24 shows details of the OTT's fail-safe brake system which include a large diameter brake rotor, brake calipers, and limit switches that, when tripped, triggers the brake to prevent model overloading or excessive motion. For personnel safety purposes, the speed of motion of the OTT is limited to approximately 0.5 deg/sec by a flow restriction circuit that is energized while the tunnel door is open.

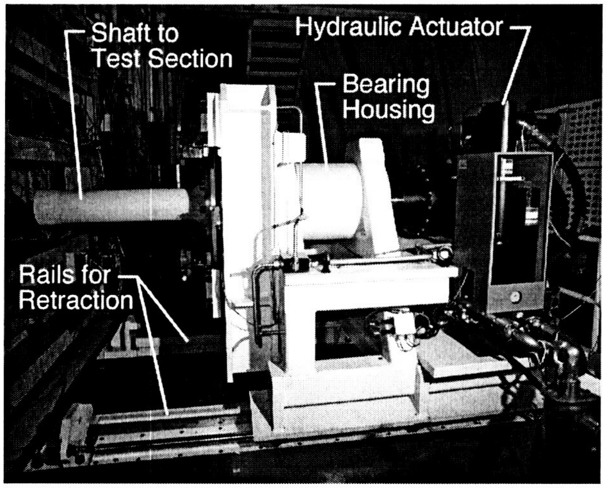


Fig 23- Side view of OTT behind test section wall.

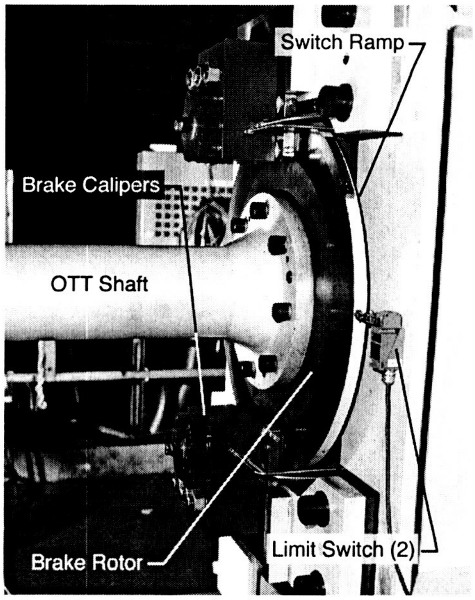


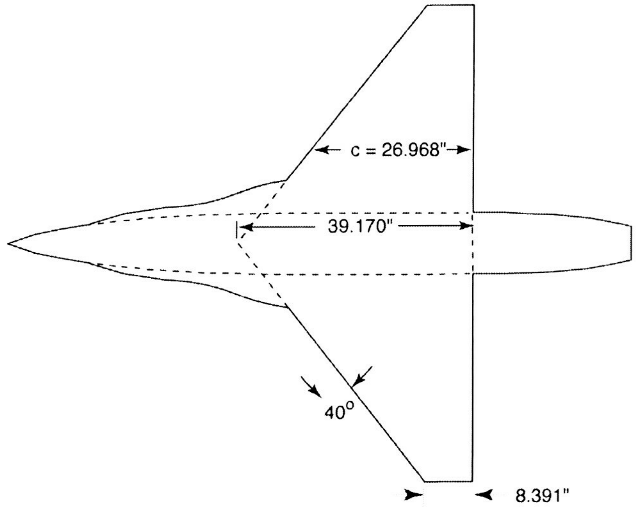
Fig. 24- OTT brake components.

Reference 18 contains a very thorough description of the OTT apparatus. This reference also documents dynamic measurements from two wind tunnel model tests that used the OTT forced pitch oscillations capability.

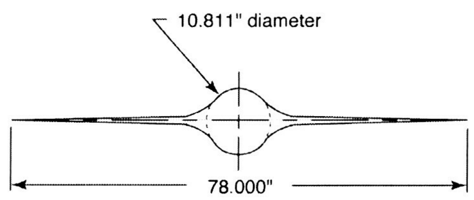
Statistical Quality Control- One of the goals that has emerged from the NASA Langley Wind Tunnel Enterprise is the pursuit of some level of statistical quality control (SQC) at all of the Center's wind tunnel facilities. One of the overall objectives of this SQC activity is to develop facility-specific techniques for monitoring and controlling certain characteristics of the wind tunnel testing process. As a result of this type of activity, it is also anticipated that process improvements will be developed. One manner of implementing the SQC plan for wind tunnel facilities is to develop models dedicated to SQC-related testing. These models are generally referred to as check-standard models. Such models are constructed with the sole purpose of monitoring pre-selected, SQC-relevant tunnel and/or model parameters. Tests are then conducted with these models at fairly regular intervals to help assess statistical control of the facility and to help identify any changes that might have occurred. During a given test, there are also many repeat measurements made to assess the stability of the measurement process.

The most fundamental SQC processes associated with wind tunnel testing involve the measurement of basic steady flow conditions in the tunnel. Work has begun at the TDT to address these fundamental measurements. Two aerodynamic models have been fabricated for the TDT to measure and assess flow properties. The first of these check-standard models is a simple conical probe that is mounted in the centerline of the TDT test section to measure flow static and stagnation pressures. Three tests using this probe have been completed at the TDT, and additional tests are scheduled to occur about once per quarter throughout each year to gather the data needed to carry out the SQC process.

One of the difficulties for the TDT with regard to SQC has been determining what processes need to be assessed to contribute to improvements in aeroelastic testing, where unsteady parameters tend to outweigh steady parameters in importance. This issue is the subject of ongoing discussions at the facility. However, a step in this direction has been the fabrication of a second check-standard model, shown in Figure 25. This model is an essentially rigid, tailless, full-span, sting-mounted airplane model with a fighter-type planform that is symmetrical about both the horizontal and vertical planes. The model was designed to TDT maximum conditions (maximum dynamic pressure condition of 550 psf and a maximum Mach number condition of 1.2 at a dynamic pressure condition of 340 psf), with a design angle of



(a) Planform view.



(b) View from upstream.

Fig. 25- Drawings of the TDT sting-mounted check-standard model.

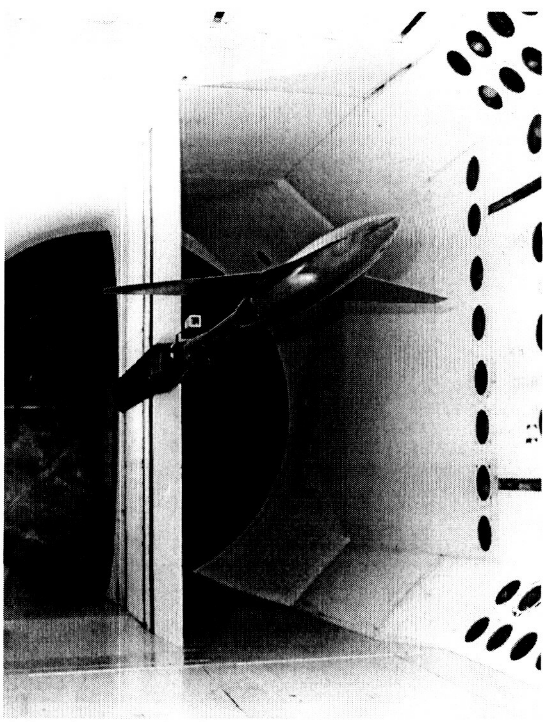


Fig. 26- Photograph of the TDT check-standard model mounted in the TDT test section.

attack range of ±10°. On-board instrumentation is light, with only a sting-mounted internal force balance and three unsteady pressure measurement transducers in the starboard wing. To date, two model entries have been completed, and preliminary assessment of the load measurements using SQC techniques has been initiated to determine the stability of the flow environment about this geometrically realistic configuration. The three unsteady pressure transducers in the wing are not part of this core SQC assessment. They were included in the model with the hope of providing some baseline unsteady data that might provide a method of applying SQC techniques more directly to the aeroelastic testing objectives of the TDT. Figure 26 shows a photograph of this model mounted on the sting-support apparatus in the TDT test section.

New Model Preparation Area- With increased use of active control testing at the TDT, particularly associated with the testing of smart material applications, the need for additional laboratory space was identified several years ago. This increased need of space is basically associated with longer preparatory activities for ever more complicated models. This need led to conversion of a portion of the previously mentioned "Building 647" to a second, and more extensive, model preparation area (MPA). This new laboratory area consists of approximately 7000 ft^2 of floor space divided into multiple rooms that are dedicated to tasks such as supporting multiple models simultaneously for laboratory ground tests, long-term storage of models, shipping and receiving of models, and storing electronic equipment associated with wind tunnel model preparation. There is also a dedicated work area for visiting personnel working on models in the laboratory. There are two locations in the model support area for installing models on permanent support systems. The first system is a previous TDT sidewall-support system, which has been replaced by the Oscillating Turntable apparatus. This system provides a reasonable representation of the actual TDT OTT sidewall-support system. It will also provide the ability to pitch a model in the laboratory in the same manner that is available in the test section (static positioning only). The second model support system is a strongback identical to the strongback previously discussed for the Building 648 MPA. As in Building 648, both sidewall- and sting-mounted models can be mounted to the strongback. A photograph of the Mars Scout model is shown mounted to the Building 647 strongback via a sting support in Figure 27.

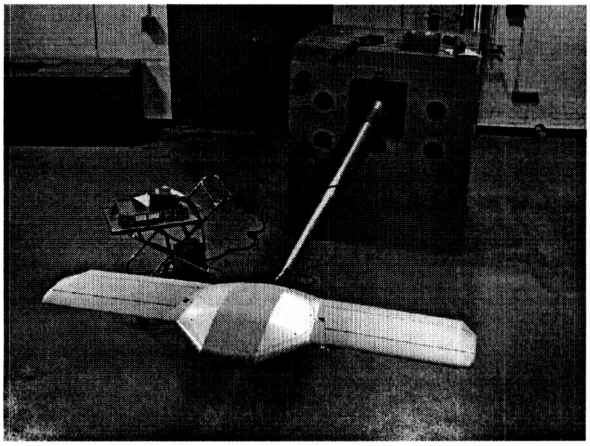


Fig. 27- Fully deployed Mars Scout model sting mounted in the Building 647 model preparation area.

Concluding remarks

Capabilities of the Transonic Dynamics Tunnel (TDT) that make it particularly suited to accomplishing successful aeroelastic testing have been described. A few recent tests of non-aeroelastic models have been specifically discussed. Finally, a review of recently completed and ongoing facility improvement projects has been presented. These facility enhancement projects have the over all primary goal of improving the suitability of the TDT to support aeroelastic testing. It is anticipated that the TDT, with its heavy gas testing capability, will continue to provide unique capabilities for carrying out and advancing the state-of-the-art in experimental aeroelasticity into the foreseeable future.

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