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**Past, Present, and Future Capabilities of
the Transonic Dynamics Tunnel from
an Aeroelasticity Perspective**

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PAST, PRESENT, AND FUTURE CAPABILITIES OF THE TRANSONIC DYNAMICS TUNNEL FROM AN AEROELASTICITY PERSPECTIVE

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Abstract

The NASA Langley Transonic Dynamics Tunnel (TDT) has provided a unique capability for aeroelastic testing for 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. Higher test medium densities substantially improve model-building requirements and therefore simplify the fabrication process for building aeroelastically scaled wind tunnel models. Aeroelastic scaling for the heavy gas results in lower model structural frequencies. Lower model frequencies tend to make aeroelastic testing safer. This paper will describe major developments in the testing capabilities at the TDT throughout its history, the current status of the facility, and planned additions and improvements to its capabilities in the near future.

Introduction

Historical perspective on aeroelasticity

Although this paper is about the NASA Langley Research Center's Transonic Dynamics Tunnel (TDT), to a very large extent the TDT is about aeroelasticity. To this end, an historical perspective on aeroelasticity is offered here as a method of introducing the TDT and to shed a great deal of light on the past importance and potential future contributions of the TDT. Aeroelasticity

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is a field of aeronautics that deals with the interaction of vehicle structural components, in terms of elastic and inertial characteristics, and aerodynamic loads that develop over the vehicle in flight. Aeroelasticity encompasses dynamic phenomena such as buffet and flutter and static phenomena such as aileron reversal and wing divergence. Dynamic phenomena are highly undesirable and can result in catastrophic instability if not eliminated during the design and development process. Aeroelasticity is predominantly thought of in terms of detrimental dynamics. However, static phenomena such as the deformation of an elastic wing under steady aerodynamic loads are also important considerations in vehicle design. Such deformations may or may not be catastrophic. Even if the deformations are not catastrophic, they can degrade desired lift and drag properties. The field of aeroelasticity also deals with methods to prevent instabilities, such as through aeroelastic tailoring or through active control methodologies. For the reader with an interest in learning more about aeroelasticity, references 1-3 are three classic textbooks on the subject.

Aeroelastic behavior has been important with respect to many technological advancements for a very long time. Reference 4 briefly describes some early, unusual encounters with aeroelasticity. Two examples of these early aeroelastic effects are problems in windmills that were empirically solved four centuries ago in Holland and some 19th century bridges that were torsionally weak and collapsed from aeroelastic effects. Many other examples exist of aeroelastic problems in civil engineering; however, the widest attention has been given to aeroelasticity in the field of aeronautics. Virtually from the beginning of flight aeroelasticity has played a role in the design or flight readiness process of new vehicles. One of the earliest examples of conscientious and beneficial use of aeroelasticity was the Wright Brothers' application of wing warping to take advantage of wing flexibility for the purpose of lateral control of their aircraft.⁵

As flight capabilities progressed rapidly in the early 20th century, aeroelasticity continued to play an important

part in aircraft design. Aeroelasticity was generally looked upon as a problem and aeroelasticians were usually consulted to fix these problems rather than being invited to join the design team early in the process to anticipate and make beneficial use of aeroelastic characteristics. This led to many expensive vehicle redesigns, as well as the loss of flight vehicles and human lives along the way. While theoretical developments progressed so that there was a continually improving understanding of aeroelasticity, the drive to achieve faster flight forced vehicles in the direction of ever lighter structures and thinner, more flexible lifting surfaces. This trend continued to make aeroelasticity an important technical field for flight. As vehicles approached and exceeded transonic speeds, the need for experimental assessment of aeroelastic behavior grew substantially because of the pronounced effect of transonic aerodynamics on phenomena like wing flutter. At the time that the transonic flight regime was being conquered, the ability to theoretically determine unsteady aerodynamics for use in the prediction of flutter did not exist. This inability to handle transonic aeroelastic effects was one of the major considerations that led to the idea of the NASA Langley Transonic Dynamics Tunnel.

History of the TDT

As the flight capabilities of aircraft advanced, wind tunnel testing capabilities were also advancing to satisfy the need. By the early 1950's several transonic wind tunnels were available. Aeroelastic experiments could then be conducted at transonic conditions, which tended to be the critical flight regime for many aeroelastic issues. A significant early effort to specifically address this need was the conversion of a 4-ft heavy gas tunnel at the National Advisory Committee for Aeronautics (NACA) Langley Memorial Aeronautical Laboratory to a 2-ft continuous flow transonic tunnel for the purpose of flutter testing.⁴ However, the lack of a particularly suitable facility in which to determine the aeroelastic behavior of new high-speed aircraft designs led A. A. Regier in 1951 to propose that the NACA design and build a large-scale, transonic facility dedicated to aeroelastic testing. Reference 4 lists the following requirements that were originally stated by Regier: 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 Regier's request for a new facility was the conversion of the Langley 19-ft Pressure Tunnel to the Transonic Dynamics Tunnel (TDT). The new wind tunnel would have all the features proposed by Regier: 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 1960.⁶ Figure 1 shows an aerial view of the current TDT. 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.

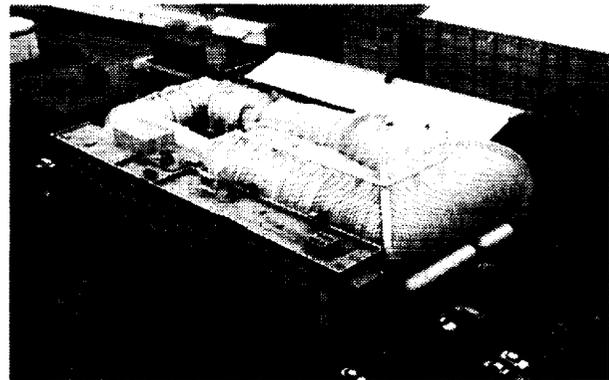


Fig. 1- Aerial photograph of the TDT.

The TDT had a significant success within months of beginning operations. In late 1959 and early 1960 the Lockheed Electra aircraft experienced two catastrophic crashes. Evidence from these crashes pointed in the direction of violent wing flutter. In an attempt to rapidly solve the Electra problem, a one-eighth scale aeroelastic model was assembled for testing in the TDT. A photograph of this first-ever, flight-vehicle flutter model tested in the TDT is shown in Fig. 2. By the time the TDT test occurred, a Lockheed engineer had identified the possibility that the Electra was experiencing a coupling between the wing structure, engine gyroscopic torques, and aerodynamic forces in a phenomena referred to as propeller-whirl flutter. The TDT wind tunnel tests showed that reduced stiffness engine supports on the outboard engines would cause the Electra to experience propeller-whirl flutter. Based on these findings, the engine mounts were strengthened on the flight vehicles to prevent stiffness reductions that could potentially develop from mount-system failures due to operational loads. Following the modifications, the aircraft never experienced a catastrophic flutter incident again. An unsubstantiated story has circulated over the years that the money saved by the aircraft industry in quickly solving the Electra propeller-whirl flutter in itself more than equaled the facility conversion costs in constructing the

TDT. Reference 7 includes a detailed summary of the flight vehicle story of this Electra whirl flutter problem.

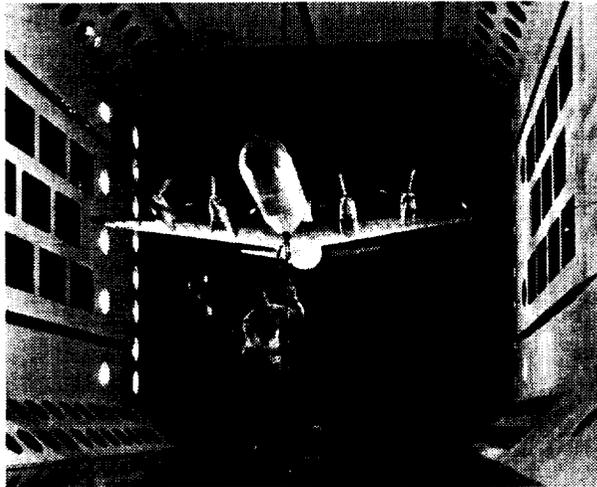


Fig. 2- Lockheed Electra model mounted in the TDT.

Over the decades, the TDT has served as a workhorse for experimental aeroelastic research and vehicle clearance testing. Testing has included such varied 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 8-15 provide overviews of testing that has occurred in the TDT over the years. Most military fighters and commercial transports developed in the United States 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.

General TDT characteristics

The 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 operating boundary of the TDT is shown in Fig. 3. The 16 x 16 ft test section allows the testing of reasonably large models. And, finally, 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 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 4 and 5 show a plan view and a test section area cross-sectional view of the TDT. These drawings show a number of the special facility features that will be discussed in more detail later in this paper.

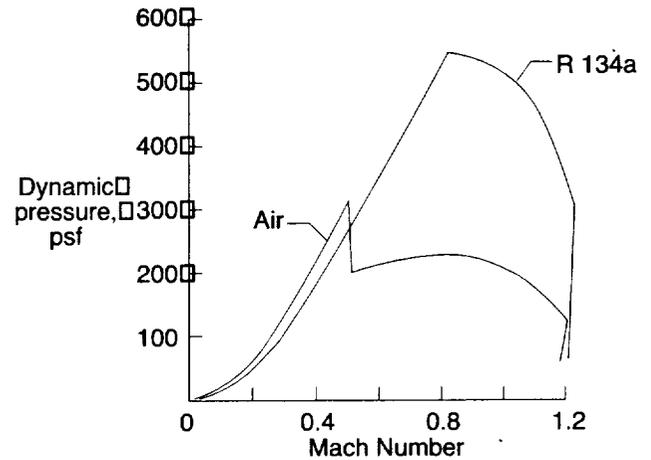


Fig. 3: TDT Air and R-134a operating boundary.

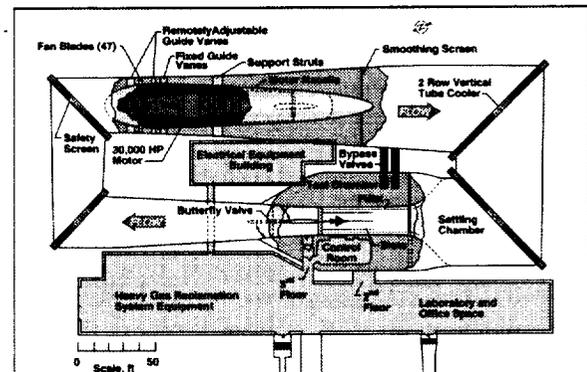


Fig. 4- Plan view drawing of the TDT facility.

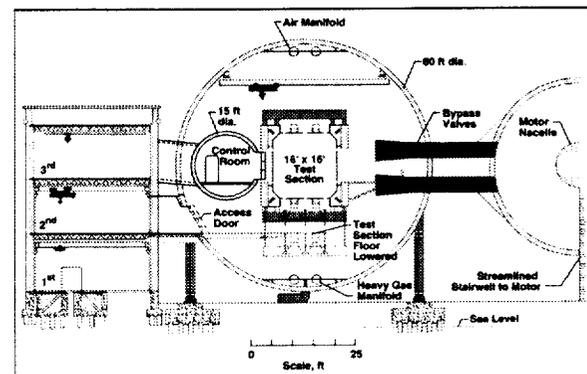


Fig. 5- Cutaway view of the TDT test section area.

Aeroelastic testing capabilities and improvements

A number of changes have occurred at the TDT in the past which have made significant improvements in the facilities ability to contribute to aeroelastic testing. Some of these improvements remain in use today, while other capabilities have been replaced due to changing needs or additional upgrades. This section of the paper discusses some of these improvements or capabilities. A few improvement projects that were contemplated in the past but not implemented are also mentioned in this section. These contemplated projects help portray the significance of the TDT's potential in trying to meet NASA's continually changing requirements to meet the nations aerospace needs in the early decades of the TDT.

Model Observation- The ability to have good visual observational capabilities of aeroelastic models was recognized from the outset in designing the conversion of the 19-ft Pressure Tunnel to the TDT. Although model instrumentation has always been a fundamental component of monitoring the behavior of aeroelastic models, visual observation may still be one of the quickest ways to make critical decisions with regard to model safety during testing. This may have been all the more true in the 1950's, during the design of the TDT, when the selection of instrumentation suitable for scaled wind tunnel model testing, especially of flexible models, was much less than what is available to the experimental aeroelastician today. The major original features of the TDT that centered on model observation were the location of the test control room and an observation dome.

Control Room- Another convenient feature of the TDT with regard to model observations is the test control room itself. The control room is the location from which the tunnel is operated and from which the wind tunnel test is directed. The TDT control room was built during the conversion from the 19-ft Pressure Tunnel to the TDT. It is physically situated directly adjacent to the test section within the pressure shell of the test chamber plenum (see Figs. 4 and 5). The primary reason for the placement of the control room was to provide good visual observations of models for improved model safety during the testing of aeroelastic models. The control room has a large matrix of observation windows allowing direct visual observation of the wind tunnel model from reasonably close proximity. This feature has proven to be very valuable because constant visual monitoring is essential to the success of aeroelastic testing due to the potentially high-risk nature of such tests. Additionally, the close proximity of the facility operators and the test engineers allows immediate, clear and concise communication in the event that model instabilities must be overcome by tunnel operations.

Observation dome- One of the more unique concepts in model observation at the TDT was a raised, streamlined observation dome near the lower right corner of the diffuser just downstream of the test section (as viewed looking upstream). This observation dome allowed the observer to protrude their head into the test section itself, protected behind the steel-and-glass housing that was the "dome". Access to this dome was not particularly comfortable. The user entered a chamber from the equipment building adjacent to the TDT structure and climbed up a ladder through a steel tube to a height where the individual's head could be placed into the dome structure. A sketch shown in Fig. 6 identifies the location of the observation dome in the TDT diffuser and shows the approximate test section area that could be viewed (shown by dashed lines emanating from the observation dome position). The observation dome provided a nice view of aeroelastic models from downstream, which added another perspective to the visual monitoring that could be made of dynamic model motions. However, the use of the observation dome was short-lived as the apparatus was quickly deemed unsafe. The increasing number of catastrophic model losses that occurred at the TDT due to the high risk of testing aeroelastic models likely led to a decision to curtail use of the dome. The physical structure of the dome remained in place until 1997. In 1997, the dome was removed based on the logic that the expansion section would be more symmetrical without the bulge of the dome and that this symmetry might lead to improved turbulence levels in the TDT. No direct verification of this was attempted.

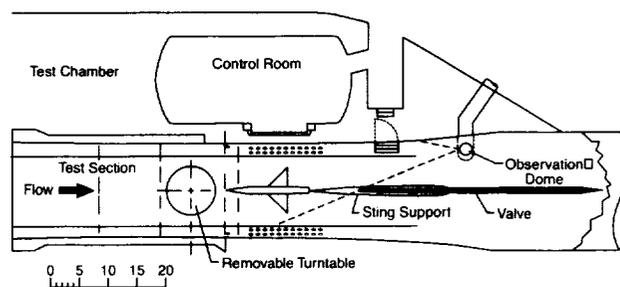


Fig. 6- Test section drawing showing observation dome.

Dynamic Pressure Capability - Although the TDT enjoyed significant early success, the continued progression of aircraft flight performance eventually began to push the realm of suitability of using the TDT for aeroelastic clearance studies. During the early 1970's, vehicle configurations had advanced to the point that it was becoming ever more difficult to scale aeroelastic models to match the lightweight, relatively flexible structures of modern aircraft. In an attempt to reduce the challenge of scaling transonic aeroelastic models, a study was conducted around 1973 to assess the possibility of increasing the TDT drive motor horsepower. The study

concluded that a fifty percent increase in horsepower was feasible with a re-wind of the drive motor. This increase in horsepower would also provide a fifty percent increase in dynamic pressure capability. This upgrade was eventually approved and was completed in 1985, thus easing the difficulty of designing and building aeroelastically scaled models for tasks such as flutter clearance of flight vehicles.

An additional TDT design study was completed in 1975 to assess the possibility of providing even greater increases in the dynamic pressure capability of the TDT while also increasing the operating Mach number to near $M=1.4$. The study concluded that it was feasible to increase both the dynamic pressure and the Mach number of the TDT. This proposed design would provide the increased capability by using a compressor system to remove some of the flow (air or heavy gas test medium) from the plenum chamber of the TDT during testing. This system was predicted to provide the capability of testing to $M=1.3$ at a cost of approximately \$10,000,000. Facility shape modifications were also proposed in order to achieve $M=1.4$, at a cost estimate of 2-3 times the financial investment required to achieve $M=1.3$. These estimated costs are the primary reason that these modifications were not pursued. The increased dynamic pressure capability provided by the TDT drive motor re-wind, and the potential additional increase in dynamic pressure and Mach number based on the two mid-70's design study proposals are shown in Fig. 7.

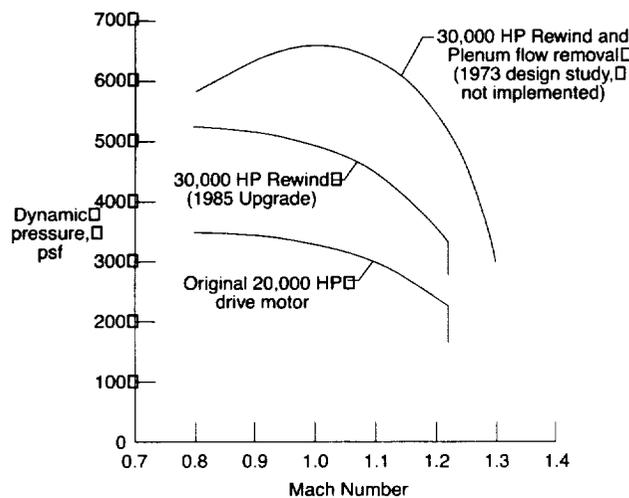


Fig. 7- TDT operating boundaries in R-12 heavy gas.

It is worth mentioning that in the 1970's there was another major TDT modification project proposed. This project related to the nation's need at that time for full-scale Reynolds number testing capability. It was proposed that a study be conducted to further increase the tunnel drive motor horsepower to 100 percent more than

its original rating, install the plenum-flow removal system discussed above, and analyze and/or modify the tunnel structure to allow testing up to pressures of four atmospheres. At these pressures, the Reynolds number provided by the increased density of the heavy gas would have provided full-scale Reynolds numbers in the TDT for many flight configurations. This project never became anything more than a suggestion that was believed to have technical merit.

Tunnel cooling system- At the same time that the TDT drive motor was upgraded, the cooling system for the TDT tunnel circuit was replaced and improved to handle the cooling requirements with the increased motor power capability. The original cooling coil system consisted of piping and heat-exchange fins mounted in a single plane immediately upstream of the corner turning vanes that are first encountered downstream of the drive motor. This position is noted in Fig. 4 and is labeled "2 row vertical tube cooler" in this figure. The new cooling coil system, constructed in 1985, consists of two sets of piping mounted side-by-side in the same general location as the previous system. A new circulating-air-cooling tower was also constructed as part of this project. In addition, a new control system was provided to improve regulation of the airstream temperature in the TDT. Water conditioned by the cooling tower is used in the piping to provide the heat transfer medium to cool the tunnel. The cooling system is not actively controlled so temperature is not precisely held; however, typical testing in the TDT occurs with temperatures in the vicinity of 105° F. Operating temperatures can rise to an about 140° F at the highest operating dynamic pressures and Mach numbers, which require the most drive motor power to achieve. This capability to provide some regulation of temperature is beneficial for aeroelastic testing in that it helps to stabilize flow conditions during testing. The ability to regulate operating temperature is also important because the material stiffnesses of the types of materials that must be used in order to build aeroelastically scaled models can be sensitive to temperatures.

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 dichlorodifluoromethane, known as R-12, for the heavy gas test medium. Testing in a heavy gas provides aeroelastic model scaling advantages. The density of R-12 is approximately four times that of air. This means that scaled models can be made heavier relative to a scaled model for testing in air. This generally makes the task of building a scaled 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.

Unfortunately, the need to eventually discontinue the use of the R-12 heavy gas in the TDT was identified at the end of the 1980's. Environmental constraints on the use of R-12 were being accelerated such 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 for use in the TDT in place of R-12. A number of gases were considered, including sulfur hexafluoride (SF₆), which has been used in some recent test facilities on an experimental basis. However, the gas chosen to replace R-12 in the TDT was 1,1,1,2-Tetrafluoroethane (CH₂FCF₃), also identified as R-134a.

R-134a is a relatively inert gas with properties similar to R-12. Like R-12, it is a virtually odorless, tasteless, invisible gas. It is incombustible within the temperature and pressure ranges that are experienced at the TDT, both for pure R-134a and for gas/air mixtures. Some of the principle aerodynamic properties of R-134a, R-12, and air are shown in Table 1. R-134a is approximately 3.5 times denser than air for identical pressure, temperature, and volume, making it a reasonably equivalent replacement for the previous R-12 heavy gas. This section of the paper describes the conversion from R-12 to R-134a and several important improvements that resulted that contribute to the efficiency of conducting aeroelastic tests in the TDT.

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

Property	Test medium		
	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

R-12 to R-134a conversion- Replacing the primary test medium for the TDT required a number of facility modifications. Conversion work began in 1990 with the original R-22 (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 starting in May, 1996 to complete the conversion process to the new operating gas, R134a. The major tasks associated with the conversion were the replacement of six 8500 cubic-feet/minute, screw-type vacuum blowers and the overhaul of a five-stage Clark recovery compressor. Photographs of these two major components of the TDT heavy gas reclamation system are shown in Figs. 8 and 9. Other changes included replacement of oil coalescing filters to keep oil in the processing equipment from migrating into the test medium, disposal of the existing liquid R-12 at the facility, and preparation of the storage tank for the new operating gas. An early description of the original TDT R-12 heavy gas reclamation system is available in Ref. 16. A more thorough description of the current R-134a reclamation system is given in Ref. 17.

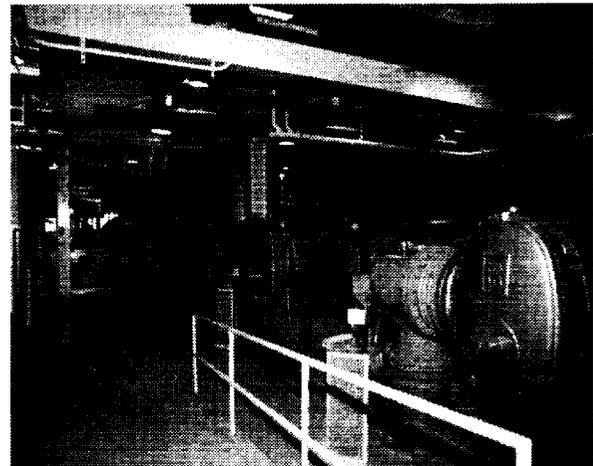


Fig. 8- TDT vacuum blowers.

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 this heavy gas conversion project, the ability to use dry, compressed air available from the air storage bottle fields at the NASA Langley Research Center was added to the TDT operating capabilities during the test medium conversion project. 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.

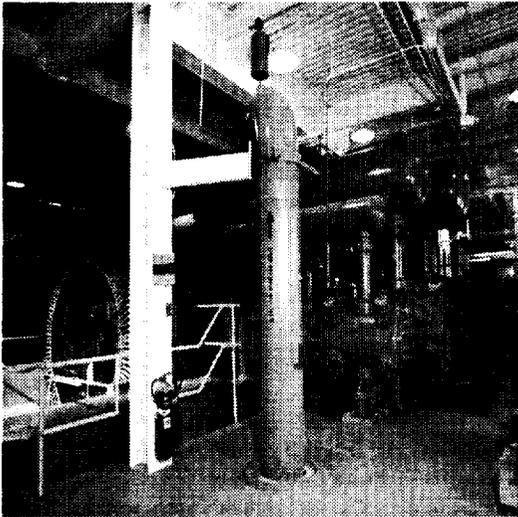


Fig. 9- Refurbished TDT recovery compressor.

Heavy Gas Reclamation System Controls- One of the major improvements made to the facility from an operations perspective was the replacement of the original heavy gas reclamation system (HGRS) controls during the 1997 heavy gas conversion project. The original HGRS control system consisted of a graphic operator's panel located in an independent heavy gas control room (Fig. 10). The system was limited in its ability to control system variables such as valve positions, monitor process variables such as temperature and pressure, and required

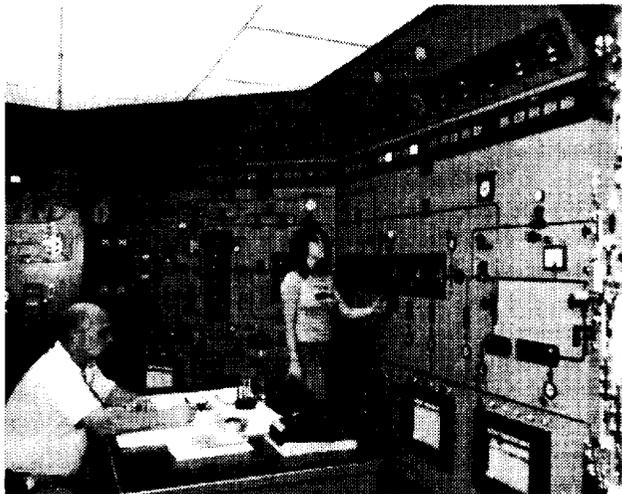


Fig. 10- R-12 heavy gas reclamation system control room.

the operators to make many routine decisions depending on the operating conditions. The entire control system was overhauled and the control room refurbished. New Allen-Bradley programmable-logic-controllers (PLC's) were installed with new graphical operator interfaces. All operator controls were moved from the graphics panel to a dedicated console and a new graphics panel was installed which displays all critical process variables (Fig. 11). A new process data acquisition system (PDAS) was installed which continuously records process variables to assess system performance and perform diagnostics.

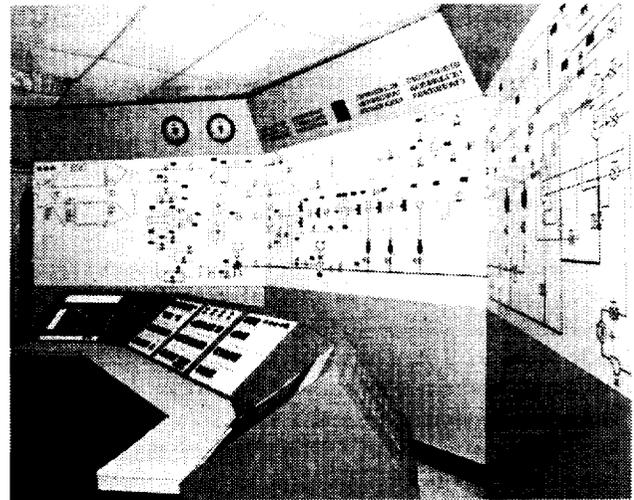


Fig. 11- Heavy gas control room as modified for R-134a.

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. 4). 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 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. The bypass valve system results in approximately a 25 percent reduction in operating Mach number and up to a 38 percent reduction in dynamic pressure in the transonic operating range. Half of these reductions occur in about three seconds. The original TDT bypass-valve system consisted of only two quick-actuating valves. This system was found to be inadequate in reducing the flow conditions, so two additional valves were added during the mid-1960's to provide the current performance capability mentioned above.

Airstream Oscillator System- Another special capability available in the TDT is a set of four oscillating vanes, referred to as the airstream oscillator system (AOS). The vane-actuator system was originally installed in the TDT during the early 1960's. When installed, the vanes are located upstream of the test section and can be driven sinusoidally to simulate atmospheric turbulence or gusts. The oscillation frequency of the vanes can be remotely adjusted from 0 to 18 Hz by an electrical control system. Vane amplitude is set mechanically from 0° to $\pm 12^\circ$. Fig. 12 is a drawing showing the vane system mounted in the TDT. As shown in the figure, two of the vanes are located on each side of the tunnel just upstream of the test section. The two vanes on either side are trained together to force identical angular movement. However, the vane set on one side can be operated in phase, or up to 180° out of phase, with the vane set on the other side of the tunnel. These vanes have been used in a number of tests for the purpose of gust load studies and active gust-load alleviation demonstrations. These vanes are removed from the tunnel circuit when not in use. Reference 18 contains a good description of the TDT AOS, and references 19 and 20 describe two different experimental studies conducted using the AOS. In the late 1980's, a new control system was assembled to provide operational control of the AOS. A wind tunnel test was conducted to verify the operations of the AOS with the new control system and to make flow-field measurements in the TDT test section at lower dynamic pressures than those previously documented.²¹

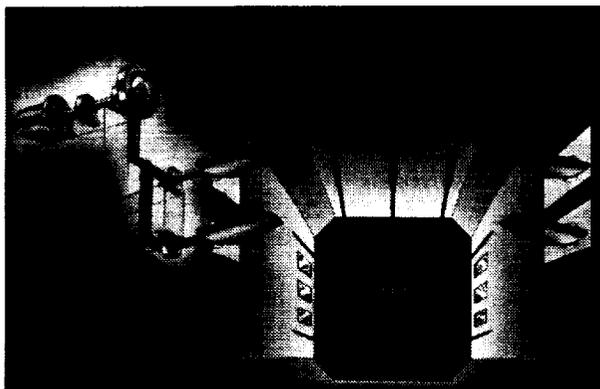


Fig. 12- View of airstream oscillator system showing cutaway of drive mechanism.

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. 4). 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. With

the isolation valves closed, only about 25 percent of the total tunnel-circuit volume has to be cleared of the heavy gas to allow access to the wind tunnel model. However, with the present system of plenum and test section isolation valves, the pressure must always remain higher on the test section side of the isolation valves. Even greater aeroelastic testing productivity could be realized if the test section pressure could be lower than the remainder of the tunnel circuit during certain gas handling processes. This is because it is most efficient to lower the tunnel pressure to about one-sixth of an atmosphere before fully recovering the heavy gas to make a test section entry. If the pressure on the test section side of the isolation valves could be lowered to one-sixth of an atmosphere while leaving the rest of the tunnel circuit at higher pressures, substantially less heavy gas would be handled. This would save a substantial amount of processing time. To this end, a design study is currently underway to determine if an upgrade to the isolation valve system can be provided to realize this productivity improvement.

Fan-Protection Screen- Although this feature does not directly result in any benefit to conducting aeroelasticity studies, there is a model debris catch screen located at the wind tunnel turning vanes just upstream of the drive motor fan blades. The provision of this catch screen recognizes the fact that aeroelastic model testing is very high risk and that the probability exists of a model failure that could damage the facility fan blades. This catch screen has protected the fan blades from model debris in the past and is considered a very valuable facility feature that contributes to the suitability of the TDT for aeroelasticity 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. For semispan support systems prior to the late 1980's, the turntable was always flush with the test section wall directly across from the test control room to allow good visual model observation. Beginning sometime during the 1960's, the circular turntable had a diameter of 16.47" and was capable of pitching models through 90° of motion (normally $\pm 45^\circ$ with respect to the freestream flow). The streamwise centerline of the sidewall-mount system is defined as "Tunnel station 72", or TS 72, (72 ft. downstream of a reference point) at the TDT. Sidewall mount systems provide the capability of testing half models from which the aeroelastic behavior of full-span vehicles can be estimated. Such models are generally easier to build and

less expensive than full-span models. However, semi-span models generally require compromises in structural, inertial, and aerodynamic similitude. An example of a semispan model mounted in the TDT test section is shown in Fig. 13.

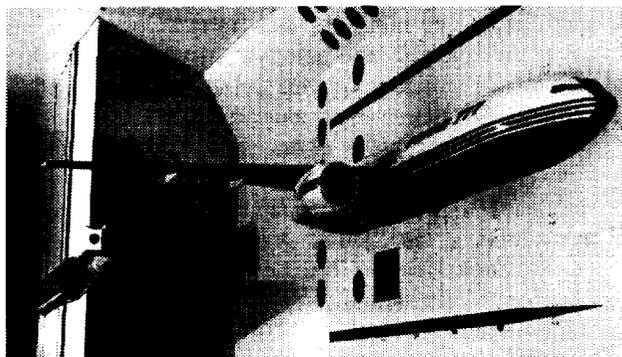


Fig. 13- Transport model mounted to TDT sidewall support system.

In the late 1980's, a second sidewall mount system, known as the retractable turntable (RTT) apparatus became available at the TDT. It was initially mounted 2.5' downstream of the previously existing, conventional sidewall turntable, so that for several years either sidewall support could be used. The advantage of the RTT was that the entire support system could be traversed in-and-out (across 3-4 ft. total in distance) with respect to the wind tunnel wall so that models were no longer constrained to mount at the wall surface. This provided the ability to design flexible mount concepts, such as model pitch-and-plunge degree-of-freedom supports, and actually allow the structure of these concepts to reside out of the test section flow beyond the normal physical tunnel-wall boundary. Furthermore, changes in the mount system, such as installing a force balance during portions of the testing, could be more readily accommodated. The RTT system proved to be a good concept; however, the fact that it was located downstream of the normal sidewall mount position meant that some large models were tested near the extremes of uniform, constant Mach number flow in the test section. To overcome this possibly detrimental aspect of testing on the RTT, the RTT was moved to the forward sidewall position (TS 72) in 1998, replacing the standard sidewall turntable.

In the early 1990's, a requirement for a mount system that could oscillate models at reasonably high frequencies led to the latest sidewall-mount system at the TDT. This new system is known as the Oscillating Turntable, or OTT. At the time of the writing of this paper, installation and checkout of the OTT had just been completed. This support system will now be the primary sidewall mount system at the TDT, replacing all previously used apparatuses. It has the ability to oscillate fairly large,

heavy models at frequencies up to 40 Hz and amplitudes from approximately 10° at low frequencies to 1° at the highest frequencies. A large hydraulic actuator provides the power to drive the OTT dynamically. Additionally, the OTT retains all of the static model positioning capabilities of the previously available turntable systems, either directly controlled by the hydraulic actuator or by an independent electric-drive system that is also a part of the OTT system. A photograph of the OTT is shown in Fig. 14 identifying key features of the OTT support system. It is anticipated that this OTT apparatus can be used to provide unsteady transonic pressure and loads data of unprecedented quality during oscillatory motions for relatively large, highly instrumented models. This type of capability holds the potential of providing data that can contribute to further advancement of unsteady aerodynamic computational capabilities, which in turn will improve aeroelastic prediction capabilities.

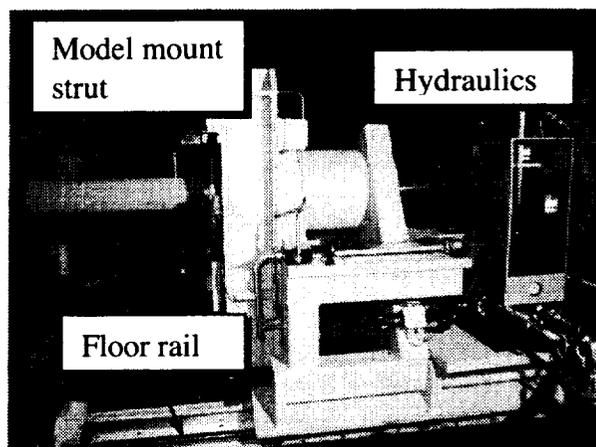


Fig. 14- OTT sidewall-support mount system

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 better aeroelastically scaled wind tunnel model, as fuselage carry-through structure and total vehicle inertial and aerodynamic properties can be modeled more accurately. Nonetheless, the sting support itself still interferes with the representation of all of these vehicle properties. The TDT sting support system is capable of traversing vertically in the test section. The sting support can also rotate in angle of attack through a range of approximately $\pm 15^\circ$. The approximate streamwise center of rotation of the sting during angle of attack variations is at TS 72. Within a tolerance of approximately ± 3 inches, this location on a sting-mounted model would stay on the vertical centerline of the test section. A sting-mounted model is shown mounted in the TDT in Fig. 15.

Crossbar Support- Another support system that was available at the TDT in the 1960's was the crossbar

support shown in Fig. 16. The crossbar support attached to the sidewall-mount turntable on one side of the test section and to a bearing support on the other side of the tunnel. The sidewall support system served as the pitch drive for this crossbar support. The advantage of the crossbar concept was that full-span, sting-mounted models could be tested to higher angles than available on the standard TDT sting support apparatus. However, the load carrying capability of the crossbar mechanism was very limiting. The high drag of the crossbar support also reduced the maximum tunnel operating condition to a Mach number of 0.9 and reduced the maximum operating dynamic pressure (at that time) by 20 to 25 percent. The apparatus was not extensively used and was apparently eliminated as a permanent facility capability due to this lack of use.

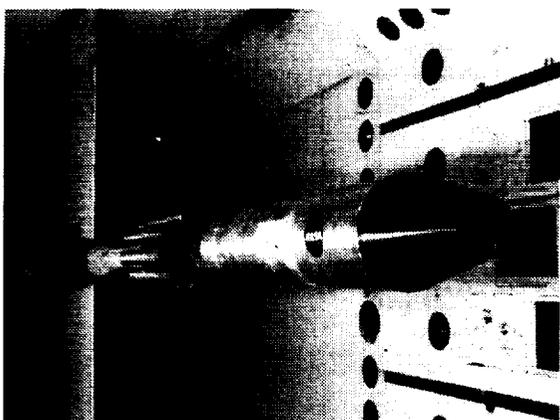


Fig. 15- Photograph of Delta III launch vehicle model sting-mounted in the TDT.

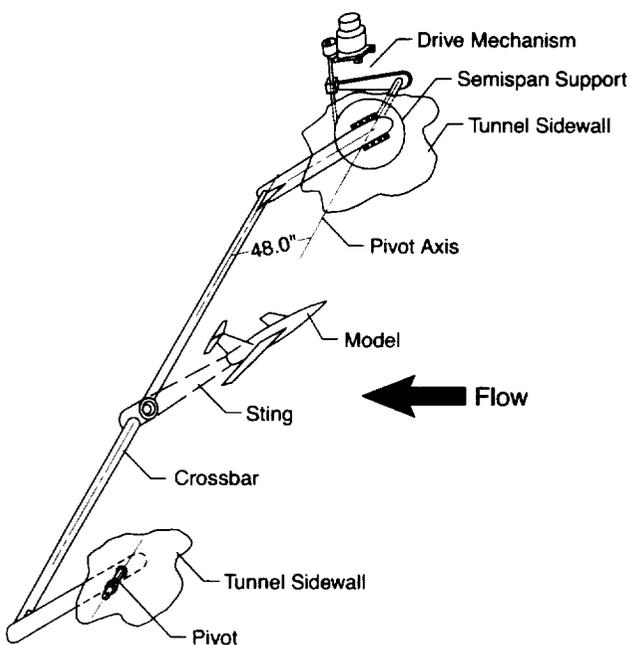


Fig. 16- TDT crossbar support system.

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. In the "static" cable-mount system, springs are mounted in one of the cables to provide cushioning in the support system so that the flight modes of the cable-supported model will simulate the actual vehicle flight stability modes reasonably well. The cable-mount system was developed at the TDT in the 1960's. A correspondence letter from an Assistant Head of the Aeroelasticity Branch, dated October 27, 1970, indicates that by this time the two-cable-mount system at the TDT had already proven its viability. Specifically, gust response studies, buffeting intensity measurements, aileron reversal measurements, dynamic stability derivative measurement, and flutter instability measurements had already been successfully completed using the cable-mount system at this time. This same letter mentions ten production airplanes that had used the cable-mount system by 1970. Furthermore, the letter states that "the cable mount has become the standard method for mounting high speed flutter models".

At one time, an active cable-tensioning system was implemented at the facility to provide the capability for testing statically unstable models which would be stabilized for testing by varying the tension in the support cables.²² This system underwent some demonstrative tests in the TDT. Figure 17 is a schematic showing a model on the active cable-mount system. The basic cable mount shown in this figure consists of a vertically oriented forward cable loop and a horizontally oriented aft cable loop. All other combinations of vertical and/or horizontal cable orientations are technically feasible possibilities. The schematic shows connecting segments of the cable loops passing across the tunnel test section perpendicular to the free-stream flow. This is only for simplicity in presenting the system in the figure. Typically, the cables actually pass through the test section walls and connect together outside of the aerodynamic flow of the tunnel using a system of pulleys.

In the early 1970's, an additional system of cables was added to the two-cable-mount system. The primary purpose of these additional cables, known as the "snubber system" cables, was to support and stabilize models during low dynamic pressure testing where the model cannot support its own weight with aerodynamic lift. This snubber system can also be manually activated during a model instability as an attempt to prevent loss of the model. During normal testing, these snubber cables are slack so as to minimize their effect on the model. The cables are tightened to perform their stabilizing function by pneumatic actuators.

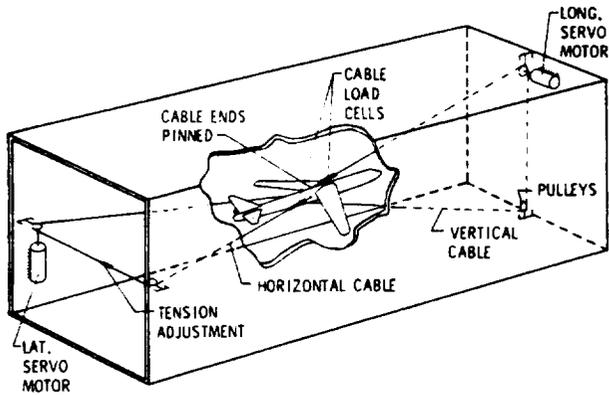


Fig. 17- Schematic of a cable-mounted model on the TDT active cable-mount system.

A photograph of a cable-mounted model is shown in Fig. 18. Ref. 23 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.

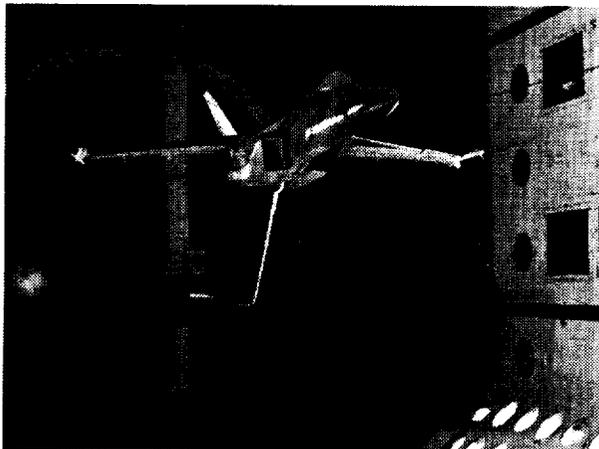


Fig. 18- F/A-18 E/F model cable-mounted in the TDT.

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 Figs. 19 and 20. Fig. 19 shows a fixed mount system that supports a testbed referred to as the Aeroelastic Rotor Experimental System (ARES). This stand and helicopter model testbed has been used for many research studies of aeroelastically scaled rotor blade systems. Reference 12 discusses other rotorcraft floor-mounted testbeds that were tested in the TDT throughout its history. Fig. 20 shows a launch vehicle model mounted on a floor turntable system. This

floor-mounted turntable is installed in the TDT test section above the normal floor. Wooden fairings are built up around this floor turntable to provide a smooth aerodynamic surface above the normal test section floor. This mount system is intended for low-speed testing of ground-mounted models. It is remotely operated and can position model azimuth with respect to the flow at any position throughout the full 360° range. This floor-mounted turntable was built specifically to support a launch vehicle ground wind loads test in the 1960's. Ref. 13 provides a summary of the ground wind loads tests that have taken place in the TDT, many of which used the floor-mount turntable.

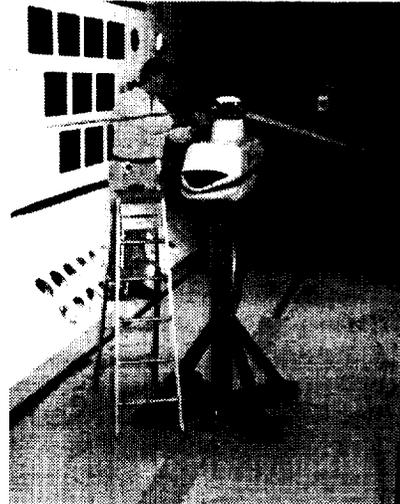


Fig. 19- ARES testbed on floor mount stand.

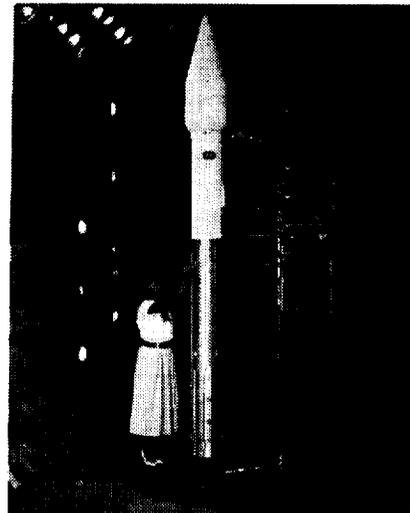


Fig. 20- Atlas II model mounted on TDT floor turntable.

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 two distinct laboratory areas for the preparation of models.

Model Preparation Area- In a building connected to the TDT, known as Building 648, there is a laboratory area that is generally used for the preparation of fixed-wing models. This laboratory area has a strongback normally used for mounting sidewall or sting mounted models. Three faces of this strongback can potentially support sidewall-mounted models and one these three faces is most suitable for supporting sting-mounted models. The laboratory area also houses a number of large, heavy surface tables. These tables are sometimes used to support wind tunnel models or to support equipment that is being used to make measurements of models supported on the strongback apparatus. 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. It is possible to directly connect up to 64 instrumentation channels from a model in this model preparation area to the computer system.

Helicopter Hover Facility- In a building adjacent to the TDT, known as Building 647, there are two areas demarcated for helicopter model preparation. The 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. Both areas are surrounded by cages made of steel that encompass the rotor system to a height approximately one-rotor diameter above the model rotor plane. The surrounding cage is open above this level. The cage is intended to capture any rotor blade debris in the event of a failure of the aeroelastically scaled rotor blades during hover testing. These test cages are located inside of a large hangar-type building, providing room to help minimize re-circulation effects of the flow about the helicopter model. In close proximity to the test cages, and within the hangar building, is a laboratory building which houses electrical and hydraulic power supplies and system controls for the rotorcraft models. This building also serves as an area for preparing rotor blades for testing and for acquiring data during hover with models mounted in the test cages.

Data Acquisition Systems

Analog era (1960-1972)- During the 1960's, the TDT Data Acquisition System (DAS) was based on hard-wired, test-specific electronics. The DAS was configured to acquire balance data and a few other channels. Data acquisition, reduction, and archival processes were based on visual observations of the model, manual recording of various instrumentation gauges, strip charts, and recording data to analog recording devices such as FM and 7-track tapes. Visual documentation was accomplished using high-speed motion film cameras that were capable of operating at 200 or 400 frames per second. The data acquisition system setup process was simple, but it required many checkout iterations to verify proper operations.²⁴ Transducer interfaces and basic acquisition requirements would often differ for each test depending on the test objectives and model complexity. Processing continuous data was limited to manually digitizing strip charts and/or manually digitizing tapes.

During the late 1960's to early 1970's, the process of standardizing on an interface from the transducer to the acquiring device was established. The result was the "B-4's." This was a servo-encoding mechanism device that interfaced directly to a transducer. It provided transducer excitation, an adjustable amplification, and adjustable filtering. The output of the B-4's was interfaced to a digital gauge, an IBM punch card recorder, or an IBM tabulator. B-4's were typically used on cable-mount model tests to measure cable loads via load cells. The B-4's had a very unique characteristic while operating. Its servo-encoding mechanisms would naturally generate an audible tone at the same frequency as the test model's oscillations. This audible tone provided the test engineers with an additional feedback mechanism while watching the model during the test. A similar front-end device called "Data Logger" was also used. For time-history analysis and frequency analysis, the analog and/or FM tapes were hand carried to the Langley central computer facility for further processing where punch card based software and batch programming reduced the data from the tapes. It would take weeks, sometimes months to digitize and reduce the test data. Typically, engineers would do all the calculations by hand using a slide-rule, an analog computer, a desktop calculator, or the standard issue hand-held HP calculator. Figure 21 shows a typical control room configuration during this period.

Sigma-V era (1972-1987)- In 1972, the first completely digital based TDT DAS was installed. This system was commonly referred to as the "Xerox Sigma-V" system. It was based entirely on "Diode-Transistor Logic" and was the first 32-bit DAS computer at Langley Research Center.²³ Other Langley wind tunnels had 16-bit computers.²⁴ The purpose of this system was to improve

the quality and increase the quantity of data that could be acquired during a wind tunnel model test.²⁵ The system was designed to reduce lengthy setup time required for each test and provide automation in the areas of front-end signal conditioning and real-time processing. The Sigma-V system began the process of real and/or near real time data processing to guide the conducting of a test. The Sigma-V had four primary functions: 1) provide automatic front-end pre-conditioning; 2) acquire and archive test and model data to magnetic tapes; 3) process and display tunnel parameter data in real-time; and 4) process and display selected model data in real-time.²⁵

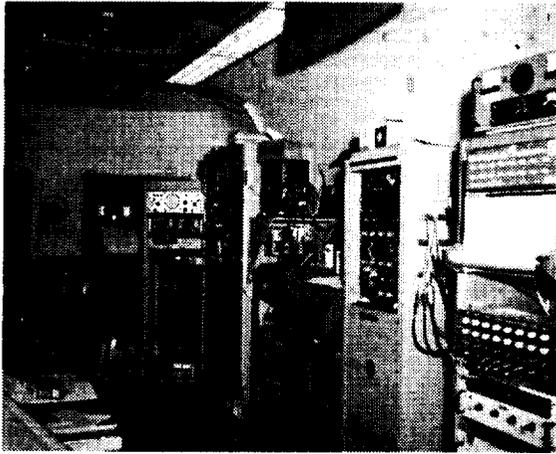


Fig. 21- Typical TDT control room configuration during the 1960's.

The Xerox Sigma-V system provided several unique capabilities. Its analog front-end system was capable of multiplexing six banks of 40 input channels and twenty fixed, preconditioned and filtered input channels to a 14-bit analog-to-digital subsystem (ADS). The maximum aggregate sample rate of the ADS was 50,000 samples per second. These signals would also be sent to a 200 Hz low bandwidth, 12-channel tape track recorder and/or a 20 kHz intermediate bandwidth analog tape recorder. The system also had the capability of measuring pressure data using up to 36 pressure-scanning valves. Each scanivalve consisted of a rotary solenoid that would scan 47 separate pressure ports per scanning valve, yielding a total of 1692 pressure measurements. The computational subsystem had a 32-bit central processing unit, which was eventually upgraded to 96 kilo-words of core memory and two rapid-access auxiliary storage disks, providing a total of twelve million bytes of direct access storage. The system also provided sequential auxiliary storage via three nine-track digital magnetic tape units. The Sigma-V computer hardware had a "four ported memory" component, which allowed for multiple input/output operations to occur simultaneously without processor intervention.²³ A light-gun, typewriter-communication terminals, digital constant input thumbwheels and toggle switches comprised the

user external interfaces to the system. All external interfaces were interfaced through a digital input/output subsystem. "Nixie" displays and a monochrome graphic display unit (GDU) located in the control room provided for communication between the researchers and the digital computer. The GDU provided graphical information on a cathode-ray tube display with refreshed vector graphics capabilities along with alpha-numeric. The user selected points or regions of interest on the GDU for post processing using a light gun. The system was not menu driven and commands were enter via a Teletype console. Programs were loaded into the machine via cardpunch readers. The user could not modify or code programs directly on the display terminals or store the programs on disk. The user would generally take an existing program and modify it for test-specific application needs. Fig. 22 shows the Sigma-V computer room and Fig. 23 shows a typical TDT test control room configuration during the Xerox Sigma computer system era.

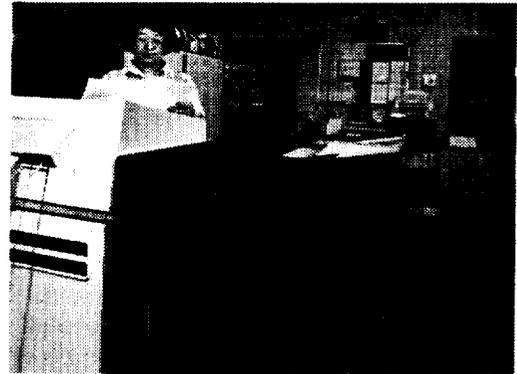


Fig. 22- Computer room during the Xerox Sigma-V era.

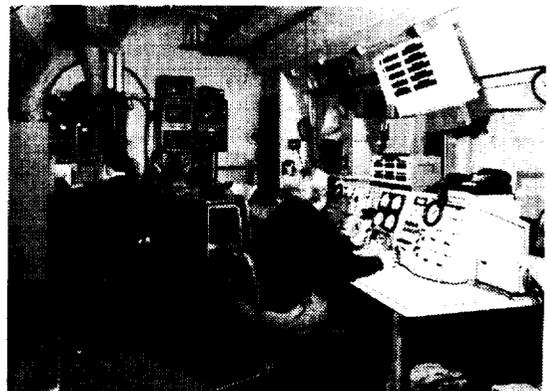


Fig. 23- Typical control room configuration during the Xerox Sigma-V era.

The Sigma-V system software was partitioned into three components, the operating system, the secondary real-time operating system, and the user applications.²⁶ The real-time OS was a real-time or batch monitor (RBM) system with prioritized internal and external interrupt

handling. The real-time system had fixed priority scheduling and fast context switching capabilities. The secondary real-time operating system, called Operating Measurement Program (OMP), provided a set of user-callable subroutines that would provide an application interface to the operating system and external hardware. The OMP provided three basic modes of operation to the user: setup, test and user services. User Applications, sometimes referred to as First Level User Programs (FLUPS), depended on OMP. One commonly used FLUP was the tab-a-point (TAB) routine. TAB recorded, printed and displayed the test point number, time code and tunnel parameters. An extended TAB would calculate, record and display quick-look average voltage for each channel, and model angle-of-attack based on shaft encoder counts. Post-point data reduction FLUP's included the following: converting data to engineering units, calculating Fourier transforms, and curve fitting transducer calibrations. The Sigma-V system also had several unique aeroelastic FLUP's: Randomdec analysis, Moving Block analysis, Fast Fourier Transforms, pressure plot distribution, time series analysis, dynamic wind deflection measurement and balance data force and moment calculations. It was estimated that the Sigma-V system had a total of 2.5 million lines of code, of which ninety-five percent of the core software was written in assembly language and the remaining software was written in Fortran-66.²³

DAMP era (late 1980's)- During late 1980's, the TDT DAS transitioned to the "Data Acquisition and Monitor Program (DAMP)" system because it needed a more reliable, secure, and modern data acquisition system as well as a system that would be easier to maintain and more physically compatible with future hardware.²⁷ The basic hardware configuration consisted of three 32-bit, 1.2 MHz MODCOMP minicomputers with 8MB of RAM connected via a share memory, 300MB hard drives and 9-track digital tape drives. Two Neff 500 front-end acquisition systems were primarily used for providing transducer excitation, acquiring and digitizing 192 analog inputs at an aggregate sample rate of 286 kHz, and a few digital I/O interfaces. FM magnetic tape recorder systems were also used to record unfiltered analog signals. The MODCOMP Data Acquisition Systems (MODACS) were the primary means of digital I/O. DAMP had scanivalve and ESP sensor control and acquisition capabilities. Magnetic tapes, disks, printers, graphic display units, and tunnel wall displays were switched between the various CPUs. DAMP was the first system designed to support the TDT and its two model preparation areas, account for computer system load-distribution issues and digitally record engineering data to a magnetic disk drive. Figure 24 shows the Damp system and the computer control room configuration.



Fig. 24a-: Front-end acquisition system during the DAMP era.

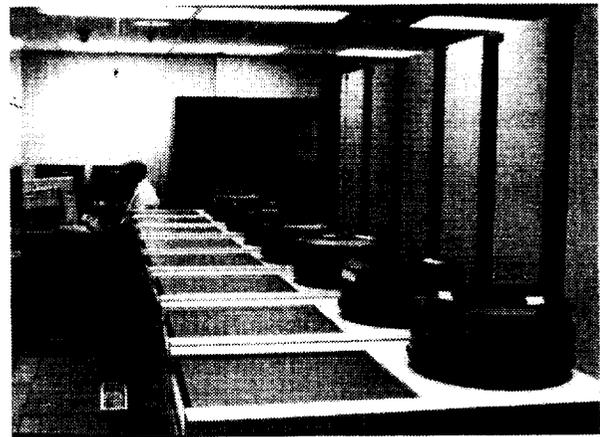


Fig. 24b- Computer room during the DAMP era.

DAMP software consisted of three basic software elements: the operating system, the data acquisition monitor/display software, and the TDT user software. The OS supported both real-time and batch processing simultaneously. A majority of the DAMP software was written in Fortran. DAMP provided real-time monitoring of the tunnel parameters and interactive control of various data acquisition functions during tunnel operations via touch-bezel screens. The DAMP software provided the same real-time and post software capabilities as the Sigma-V via user-callable subroutines. TAB, and extended TAB files were written to tape in engineering units. DAMP had an interactive "Test Specification" text database application for configuring the system. DAMP also provided a mechanism for a two-minute raw data circular archive file and a 15 minutes continuous data-taking mode.

Present Data Acquisition System- The present TDT DAS is a point-based time-series data acquisition system designed to support various types of aeroelastic and static wind tunnel tests. Its primary purpose is to provide TDT

customers with an accurate, useable and reliable system that acquires, archives, processes, displays and distributes model data, calibration data and tunnel data. The TDT DAS supports two facilities, the Transonic Dynamics Tunnel and the Model Preparation Area (MPA). The design of the TDT DAS was based on an enhanced modification of an "Open System Standard" design called *Open Architecture (OA)* which was developed by NASA Langley's Data System and Instrument Support Branch during the early 1990's.^{28, 29} The TDT DAS is composed of two primary entities: the hardware components and the software components. These entities define the DAS interfaces, capabilities and operational boundaries. Figure 25 shows the control room and the computer system for the OA-DAS system.

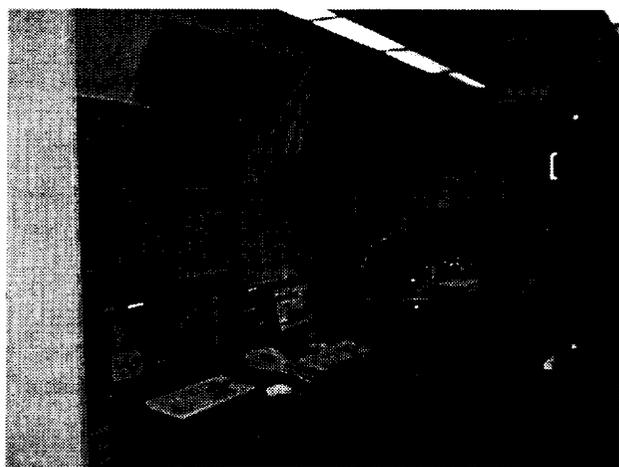


Fig. 25a- Present TDT control room configuration.

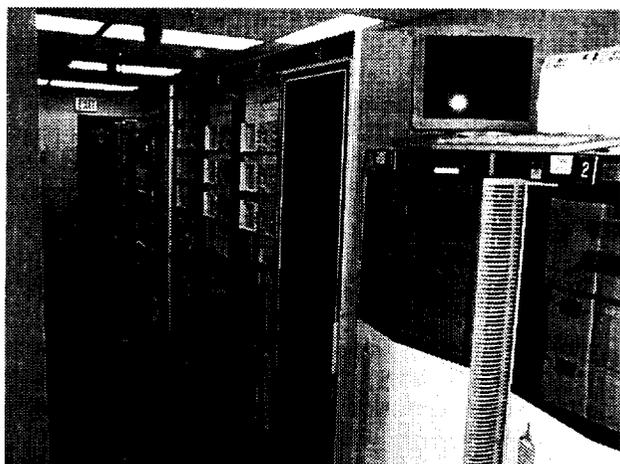


Fig. 25b- Present computer room.

Data Acquisition System Hardware- Figure 26 shows a system block diagram of the TDT DAS. The hardware components are comprised of two basic building blocks:

the acquisition subsystem and the computational subsystem.

Acquisition Subsystem- The first hardware building block consists of two acquisition components: the NEFF-500/600 Analog and Digital Front End (NEFF) and the Pressure Systems 8400 Electronic Pressure Scanner System (ESP). The NEFF is a computer controlled 256-channel analog-to-digital acquisition subsystem with transducer excitation and digital inputs capabilities. This system provides fully programmable differential pre-gains and post-gains, linear-phase filtering ($f_c = 1, 50, 200$ or $1,000$ Hz) for each analog input with simultaneous sample-and-hold preamplifiers for a 16-bit analog to digital converter. The NEFF has an aggregate sampling rate of 300,000 samples per second, which typically provides data acquisition rates of about 1,000 samples per second for 256 channels. Note that the 256 channels are shared between the tunnel system and the MPA. The ESP is a modular stand-alone data acquisition system that supports electronic pressure scanners and pressure standards complemented with on-line calibration. The NEFF and the ESP define the external interface to the TDT DAS.

Computational Subsystem- The second hardware building block consists of two independent sets of distributed computer systems that provide real-time monitoring, control, computation, display, and archive functions. One set supports the TDT and the other set supports the MPA. Each set consists of four computer systems, an 88K-Modcomp computer system, a SGI Power Challenge-L system, a 4100 Digital Alpha Server and a Windows NT workstation. All of these systems are connected together via a 10/100BaseT switched network and a 150Mbit high-speed fiber-optic reflective memory network (SCRAMNet), for distributing real-time data. The 88K-Modcomp computer system was integrated into the TDT DAS in 1993 and serves as the central controller. It has four 25-MHz Motorola 88100 CPU's (88K) with 96 MB of random access memory. The Modcomp interfaces with the acquisition components via a parallel interface for the NEFF and an IEEE-488 GPIB for the ESP system. The Modcomp executes the OA software, which performs real-time acquisition, computation, display, archival, and distribution of data. This data is distributed to the SGI Power Challenge for near real-time data analysis via SCRAMNet and is simultaneously archived to a RAID Server where a Digital Alpha Server executes post-point and/or post-run processing routines. The NT workstation provides the test engineer with graphical user interface windows for controlling the entire DAS and accessing the data. The software section of this paper describes the key functions and capabilities of the OA software.

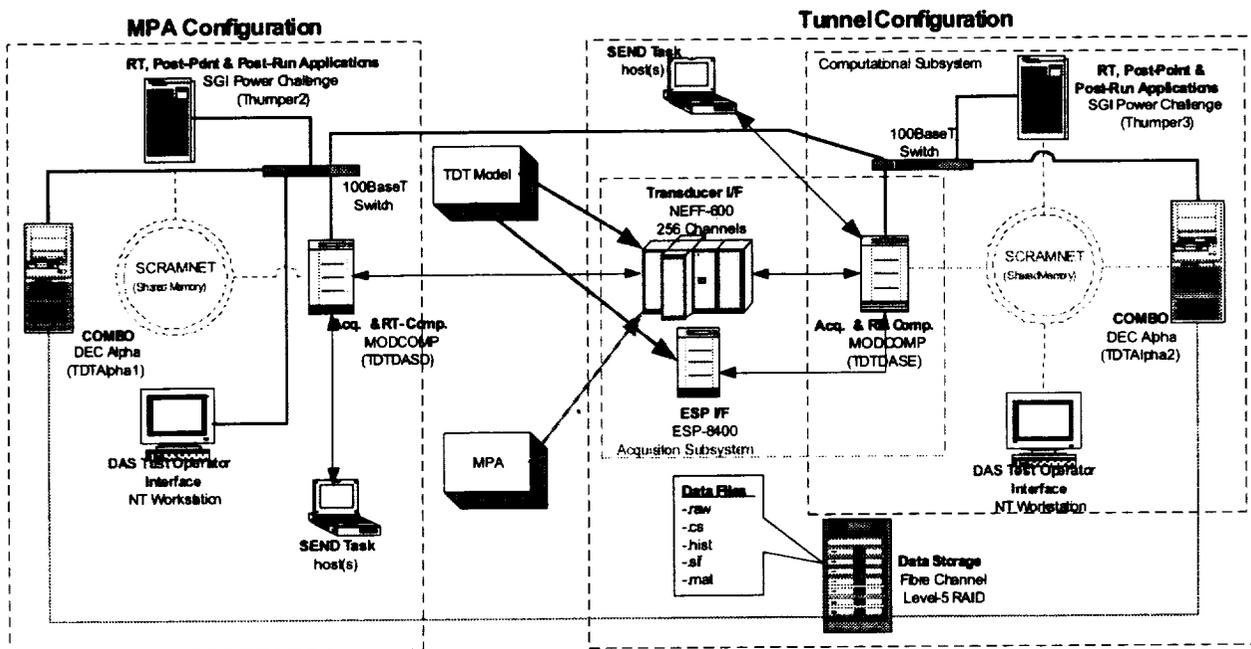


Figure-26: System Block Diagram of the Present TDT DAS

Data Acquisition System Software- The operation of the system is under the control of the test engineer through the use of TDT DAS "Open Architecture" software. The TDT DAS OA user interface is X-based and menu driven. The TDT DAS OA software provides real-time and post-point capabilities by integrating and controlling all TDT DAS hardware through industrial standard hardware interfaces, such as VME, IEEE-488, and SCSI. The real-time features of the OA software execute on the Modcomp computer system running a real-time UNIX operating system called REAL/IX. The OA software is based on approximately two million lines of structured FORTRAN and C code.

The TDT OA DAS software provides several capabilities. These capabilities can be grouped into four categories: setup capabilities, real-time capabilities, post-point capabilities, and post-run capabilities. The setup sequences are performed by the test engineer using an Excel based template called the "Test Setup Executive." It provides the users with an efficient and effective interface for configuring the TDT DAS from their desktop computer. The real-time capabilities are the continuous acquisition, display, archive, distribution and control of NEFF data, ESP data, calibration data and setup information. The Post Point and Post Run capabilities are performed by a Fortran application called COMBOTDT and a Matlab application called TDT_analyzer. COMBOTDT is a report-processing program that reads, validates, and processes every RAW data file. TDT_analyzer is a Matlab[®] based application that

provides a collection of commonly required plotting and dynamic analysis functions of channel data in a user-friendly, interactive and batch processing environment.²⁹

Future directions

The TDT is anticipated to continue to provide a unique capability for testing aeroelastic model systems well into the foreseeable future. Several specific tasks are currently planned to sustain and improve the test capabilities of the TDT. This section discusses ongoing planning activities for projects aimed at improvements in wind tunnel data quality, testing productivity, model preparation capabilities, and data acquisition.

Statistical Quality Control- One of the goals that has developed out of the Wind Tunnel Enterprise at the NASA Langley Research Center is to pursue some level of statistical quality control (SQC) at all of the Center's wind tunnel facilities. The overall objectives of this activity in SQC are 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 carrying out SQC 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 a particular testing objective in mind.

Tests are then conducted with these models at fairly regular intervals to help assess statistical control of the facility and to help identify if anything appears to have changed. 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. One test using this probe has been completed at the TDT, and additional tests are scheduled to occur about once per quarter throughout the 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. The 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 Fig. 27. This model is an

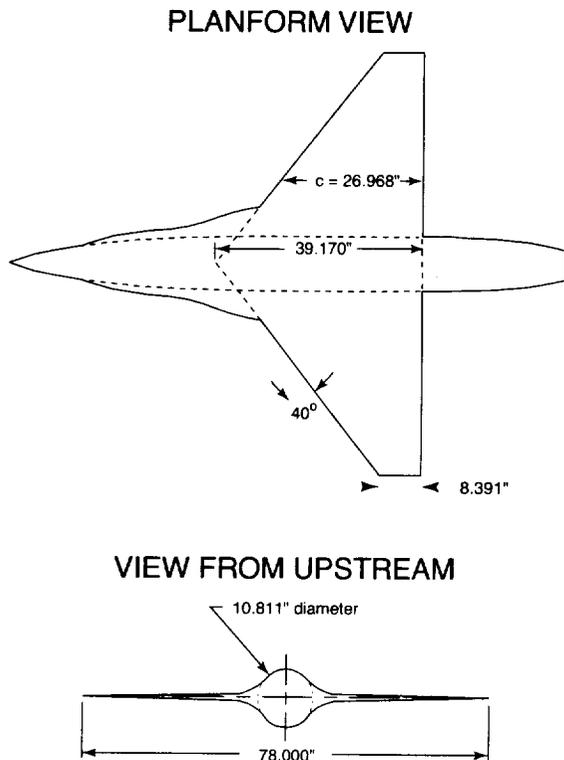


Fig. 27- Drawings of the TDT sting-mounted check-standard model.

essentially rigid, fighter-type airplane model that is symmetrical about a horizontal plane and is intended to be mounted from the sting support apparatus in the TDT. The fabrication of this model has been completed; however, the first test has not yet been conducted. This model will provide load measurements made using an internal force balance. These load measurements can be assessed using SQC techniques to determine the stability of the flow environment about a geometrically realistic configuration. Additionally, three unsteady pressure measurement transducers are being installed on one of the wings of this model to provide some baseline unsteady data that might provide a method of applying SQC techniques more directly to the aeroelastic testing objectives of the TDT. Figure 28 shows this full-span model mounted on the sting-support apparatus in the TDT test section.

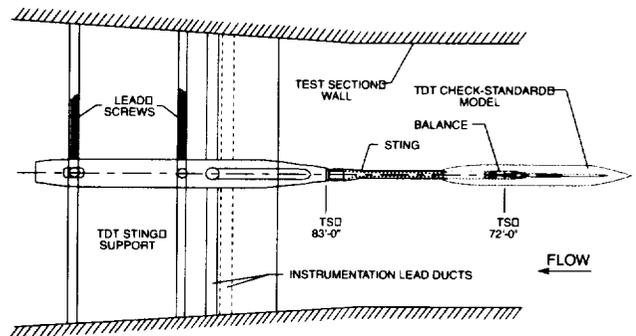


Fig. 28- Check-standard model shown on sting mount.

Productivity Improvement Projects- A number of modifications have been proposed for the Heavy Gas Reclamation System (HGRS) at the TDT to improve productivity of the facility. A NASA facility construction project has been approved to implement these improvements. This work is planned to begin around October 2000 with the facility shutting down for 2.5 months beginning in March 2001 to accomplish the actual system modifications. These modifications will lead to simplification of some operational procedures, and will provide direct time savings during several operational procedures. Two of the more significant impacts will be: 1) start-up time at the beginning of heavy gas operations for a given test will be reduced by as much as four hours; and 2) there will be even less 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. It is believed that these improvements to the HGRS system, in conjunction with appropriate operational procedures, can prevent these lengthy delays. Ultimately, these improvements to the HGRS will result

in more productive aeroelastic testing, potentially reducing test costs to facility users through reduced occupancy times required.

Another NASA facility project has been approved to automate the 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, it is anticipated that control of fan-blade pre-rotation vanes and test section re-entry flaps may also be implemented to provide further automation in changing wind tunnel test conditions. Finally, improvements may also be made in the control and setting of the sting-support apparatus and the sidewall, 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, aerodynamic-measurement models that the TDT sometimes supports. Likewise, testing of low-risk, "rigid" models for the measurement of unsteady aerodynamics will proceed more efficiently with these facility automations. 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. This project is still being planned; however, it is anticipated to occur in 2002.

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 has led to a facility construction project to convert a portion of the previously mentioned "Building 647" to a second, and more extensive, model preparation area (MPA). This new laboratory area consists of multiple rooms 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 will also be a dedicated work area for visiting personnel working on models in the laboratory. There will be two locations in the model support area for installing model support systems; however, it remains unclear at this point as to what the model support systems will look like because the construction project could not fully fund model support systems in the new MPA. As a minimum, the RTT sidewall-support system, which has recently been replaced by the Oscillating Turntable, will be installed in the MPA. This will provide a reasonable representation of the actual TDT 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. This will be a new laboratory capability for the TDT.

Future Data Acquisition System- Table 2 is presented as an attempt to summarize the TDT data acquisition systems of the past, present, and future. This table provides information that illustrates the differences in the many TDT DAS capabilities and configurations. It can be stated that the primary requirement has been and will continue to be that the TDT DAS acquire, archive, display and process continuous time-series data in real-time. It is planned within the next two years that the TDT DAS will undergo a revolutionary technology enhancement to improve the overall test process, data quality, and to reduce the total cost of conducting a test. The future DAS will be more intelligent and informative. It will be able to determine if signals are reasonable and may be able to assess if testing is following a normal process. It should be able to notify the operators of model and DAS problems and provide suggestions about how they may be corrected. The future DAS will be able to simultaneously acquire at least 256 channels of analog data with each channel being set to a different cutoff frequency and group sampling rate.³⁰ The maximum sampling rate per channel is expected to be 6 kHz for a 256-channel configuration. The future TDT DAS software will be based on the object-oriented programming languages C++ and JAVA. The future TDT DAS should be capable of controlling model surfaces, and running complex control and analysis algorithms in real-time. It will have an interface to simultaneously validate Computational Fluid Dynamics (CFD) algorithms and Flutter Prediction Algorithms in real-time. It will have the capability of providing real-time 3-D graphical model rendering. The future TDT DAS will have a higher reliance on various video measurement techniques such as the Model Deformation and Video Angle of Attack test techniques. All of these capabilities will be possible because of the low cost and ever improving PC technologies.

Concluding remarks

Capabilities of the Transonic Dynamics Tunnel (TDT) which make it particularly suited to accomplishing successful aeroelastic testing have been described. Developments at the facility throughout its history have been discussed in an attempt to capture past changes at the TDT and to summarize its present status. Planned future developments for the TDT wind tunnel facility also have been presented. These proposed projects have the primary goal of establishing enhanced 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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Table 2- TDT DAS Past, Present and Future Capability Summary

ERA ⇒ Characteristics ↓	1960'S MANUAL DAS ERA	1970'S XEROX SIGMA ERA	1980'S DAMP ERA	1990'S OPEN ARCHITECTURE ERA	2000'S NEXT GENERATION TECHNOLOGY ERA
Acquisition Front-End Subsystem	<ul style="list-style-type: none"> 12 Analog Input channels Nanometers Data loggers B-2's and B-4's FM tapes Seven Track tapes Strip Charts Manually digitize film 	<ul style="list-style-type: none"> 260 Multiplexed Analog Input Channels 50KHz Aggregate Sample Rate Active Filters with 14bit ADC Scanivalues FM tapes 	<ul style="list-style-type: none"> 192 Analog channels with 286KHz Aggregate Sample Rate 8 channels of Digital I/O Scanivalues ESP sensor control 	<ul style="list-style-type: none"> 256 Analog channels of Simultaneous Sample and Hold with 16bit DAC channels and a 300KHz Aggregate Sample Rate. 16 channels of Digital I/O ESP sensor control 	<ul style="list-style-type: none"> 256 Analog channels of independent simultaneous 16bit ADC with programmable digital filters. 6KHz Sample Rate per channel. Support Digital Image Processing Wireless interface to model
Computational Subsystem	<ul style="list-style-type: none"> Hand calculations Desktop Calculator Analog Computer External Central Computing Facility 	<ul style="list-style-type: none"> 32 Bit CPU Xerox Processor 32K Word RAM ⇒ 96K word RAM 12MB of Disk Storage Nine Track Digital tapes 	<ul style="list-style-type: none"> 32 Bit, 1.2MHz MODCOMP processor 8MB of RAM 300MB of Hard Drive Space Nine track digital tapes Active Filters with 14bit ADC FM Tapes 	<ul style="list-style-type: none"> Quad 32 Bit, 25MHz MODCOMP processor with 96MB of RAM 10GB of Hard Drive Space with 128 MB SCSI Cache Active Filters with 16bit ADC RT Frequency Analysis 	<ul style="list-style-type: none"> Quad - 1.5GHZ 64Bit Processors base on PC Technologies with 400MHz System Buses 4GB of Memory 1000 GB RAID storage with off-line storage capability
Software Subsystem	<ul style="list-style-type: none"> No software 	<ul style="list-style-type: none"> Real-time or Batch Monitor w/Prioritized Interrupts 80% Assembly, 20% Fortran OMP, FLUP 	<ul style="list-style-type: none"> Max-32 System Simultaneous Real-time and Batch Monitor Operating System. 60% Fortran & 40% Assembly OMP, FLUP Required "Test Specification Configuration File" 	<ul style="list-style-type: none"> Real-time Unix Operating System 95% Fortran, 5% Assembly & C Distributed Share Memory - SCRAMNET 2 million lines of code. System Interfaces to Windows NT and Digital Alpha Server. Support for RT, Post-Point and Post-Run user calculations. 	<ul style="list-style-type: none"> Software design will be platform independent. Real-time Windows & Linux Operating System 60% C++, 25% JAVA, 15% Labview & MATLAB Distributed DAS Architecture.
User Interface	<ul style="list-style-type: none"> Reading gauges, dials and meters 	<ul style="list-style-type: none"> Nixie Displays Shaft encoders, thumbwheel Monochrome graphic display unit Light-gun pointer Tel-type printer & Punch cards 	<ul style="list-style-type: none"> Touch-Bezel Screen Graphical Display Unit Tunnel Wall Display Line Printer 	<ul style="list-style-type: none"> Test Setup Application based on Excel Spread Sheet Application. Menu and Mouse Driven Interface, X Windows and Windows NT interface. Display data to various interfaces 	<ul style="list-style-type: none"> Menu Driven and Mouse Driver Graphical User Interface Voice Activated.
Unique Features	<ul style="list-style-type: none"> High Speed Motion Cameras 	<ul style="list-style-type: none"> TAB & Extended TAB Support several Aeroelastic Applications 	<ul style="list-style-type: none"> Point-based System Reliable, Secure & Modernized 2 minute circular archive 15 minute continuous data taking mode Extended Aeroelasticity Applications 	<ul style="list-style-type: none"> Same unique features as DAMP Support for MPA & Tunnel simultaneously Uses standard industrial interfaces such as SCSI, VME, IEEE-488 and 10Base T. 	<ul style="list-style-type: none"> Data interface to validate Theoretical Models in real-time. Real-Time Video Image Processing Real-Time flutter prediction and control

