THE NEW HEAVY GAS TESTING CAPABILITY IN THE NASA LANGLEY TRANSONIC DYNAMICS TUNNEL

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Abstract

The NASA Langley Transonic Dynamics Tunnel (TDT) has provided a unique capability for aeroelastic testing for over thirty-five years. The facility has a rich history of significant contributions to the design of many United States commercial transports and military aircraft. The facility has many features which contribute to its uniqueness for aeroelasticity testing; however, perhaps the most important facility capability is 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. The heavy gas also provides other testing benefits, including reduction in the power requirements to operate the facility during testing. Unfortunately, the use of the original heavy gas has been curtailed due to environmental concerns. A new gas, referred to as R-134a, has been identified as a suitable replacement for the former TDT heavy gas. The TDT is currently undergoing a facility upgrade to allow testing in R-134a heavy gas. This replacement gas will result in an operational test envelope, model scaling advantages, and general testing capabilities similar to those available with the former TDT heavy gas. As such, the TDT is expected to remain a viable facility for aeroelasticity research and aircraft dynamic clearance testing well into the 21st century. This paper describes the anticipated advantages and facility calibration plans for the new heavy gas and briefly reviews several past test programs that exemplify the possible benefits of heavy gas testing.

Nomenclature

a	speed of sound, ft/sec
b	reference length, ft
C_p	constant-pressure heat capacity coefficient, $\frac{\text{Btu}}{\text{lb} \cdot \text{R}}$
C_v	constant-volume heat capacity coefficient, $\frac{\text{Btu}}{\text{lb} \cdot \text{R}}$
m	generalized mass, slugs
M_g	molecular weight
p	static pressure, lb/ft^2
p_o	stagnation pressure, lb/ft^2
R	gas constant, $\frac{\text{ft}^2}{\text{sec}^2 \cdot \text{R}}$
$\overline{R}$	universal gas constant
T	temperature, R
T_o	stagnation temperature, R
V	velocity, ft/sec
x	purity (fraction of heavy gas)
γ	ratio of specific heats
ρ	fluid density, $\text{lb} \cdot \text{sec}^2/\text{in}^4$
ω	frequency, rad/sec

Subscripts

a	air
h	heavy gas
w	wind-tunnel model
v	full-scale vehicle
l	local condition
x	gas mixture

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 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 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 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] An early description of the initial heavy gas processing system for the TDT can be found in Ref. 7. Figure 1 shows an aerial view of the TDT. The TDT represented a significant advancement in aeroelastic testing capabilities, primarily because of its large size, heavy gas test medium and transonic speed capabilities.

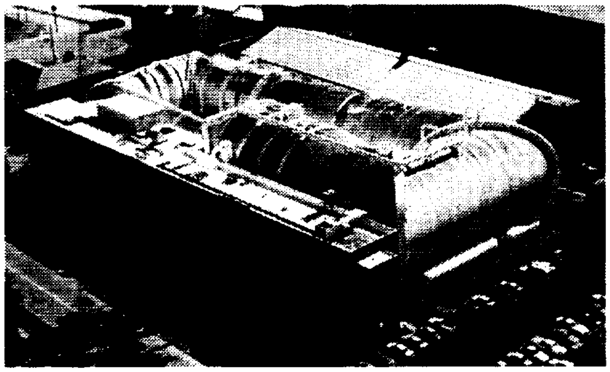


Fig. 1- Aerial photograph of the TDT.

The TDT had a significant success within months of coming on-line. 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 flutter clearance 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 a 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 stiffened on the flight vehicles and 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.

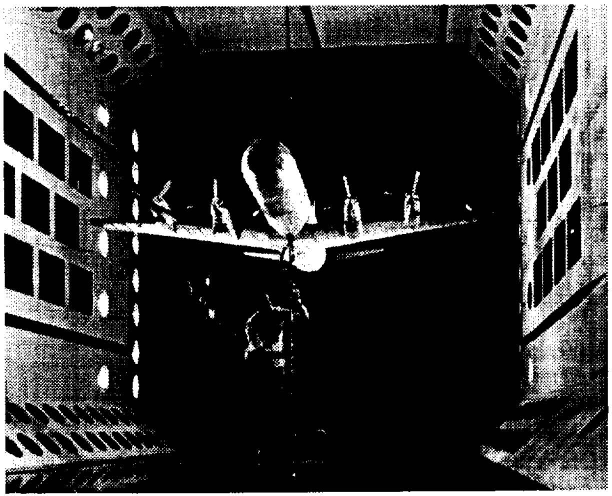


Fig. 2- Lockheed Electra model mounted in the TDT.

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 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 8-10 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.

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. In the early 1980'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 modern aircraft. In an attempt to reduce the challenge of scaling transonic aeroelastic models, an upgrade to the TDT facility was accomplished which increased the drive motor horsepower to a level which resulted in a 50 percent increase in the dynamic pressure capability. This upgrade was completed in 1985, thus easing the difficulty of designing and building aeroelastically scaled models for tasks such as flutter clearance of flight vehicles.

Heavy Gas Conversion

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 (SF_6) which has been used in some recent test facilities on an experimental basis. However, the gas of choice for replacing R-12 in the TDT was decided to be 1,1,1,2-Tetrafluoroethane (CH_2FCF_3), also identified as R-134a.

R-134a is a relatively inert gas with properties fairly similar to R-12. Like R-12, it is an odorless, tasteless, invisible gas. It has been determined to be incombustible within the temperature and pressure ranges which it will experience at the TDT, both for pure R-134a and for gas-air mixtures. Some of the principle properties of R-134a, R-12, and air are shown in Table 1. The data in this table shows that the properties of R-134a are relatively close to R-12. It is this similarity to R-12 that was considered critical to the continued viability of the TDT because of the great advantages that are realized in scaling and testing aeroelastic models (discussed in more details in the following section).

Table 1: A comparison of some properties of R-134a, R-12, and air.

	Test medium		
Property	R-134a	R-12	Air
M_g	102.03	121.00	28.97
γ	1.13	1.14	1.40
a, ft/sec	540	505	1116

At the time of the writing of this paper, the project to convert the TDT from an R-12 testing capability to an R-134a testing capability is ongoing. The conversion is planned to be completed in July 1997, at which time a calibration effort will begin (discussed below) for the new operating test medium. Following the calibrations, the TDT will return to operational status with both air and R-134a heavy gas operational capabilities available. Even during this shutdown period, the demand for the TDT clearly remains high as exhibited by a full test schedule for approximately 13 months after the facility returns to normal operations and only a few weeks of currently undefined test time during the first 24 months of operations.

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 Mach numbers above the speed of sound, reaching M = 1.2 in air and an estimated M = 1.1 in the new heavy gas, R-134a. 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. 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

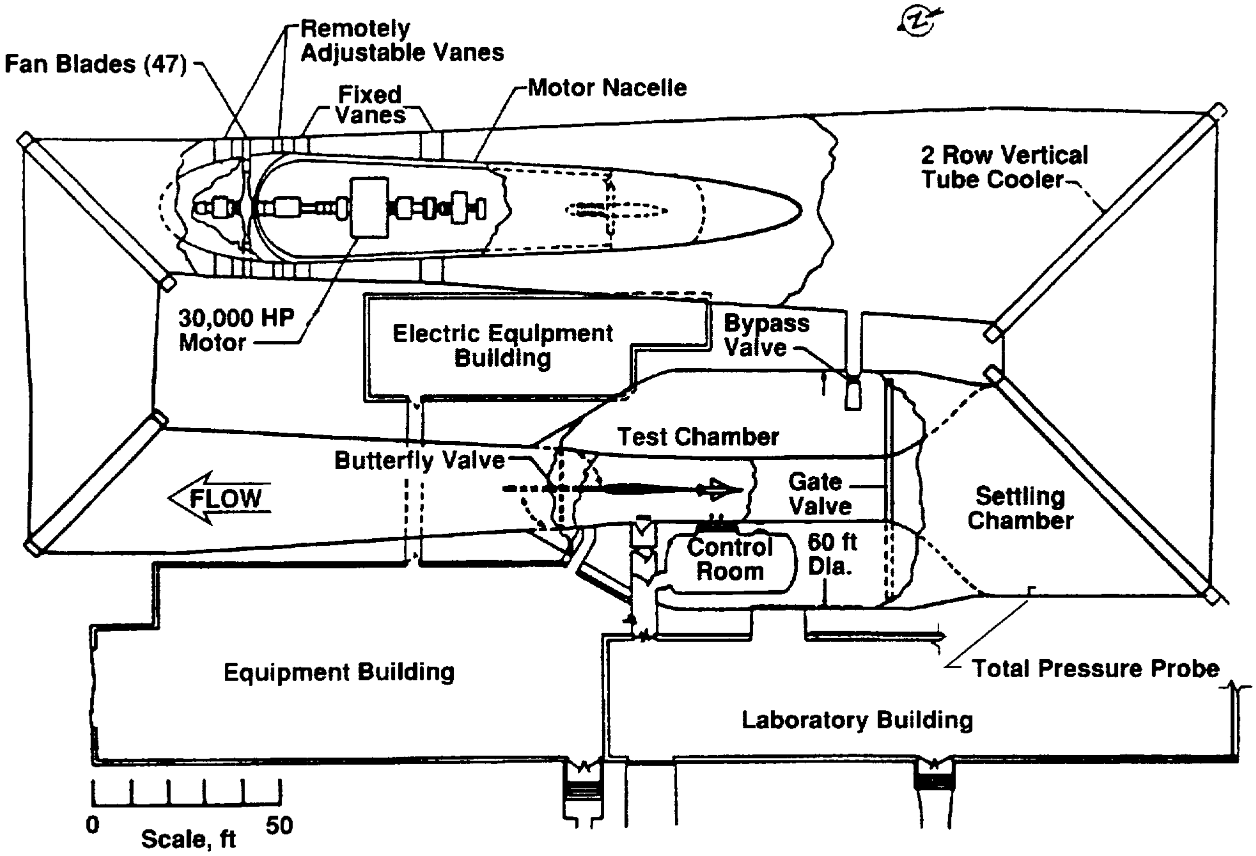


Fig. 3- Plan view of TDT facility.

number of other facility features that help make the TDT particularly suitable for aeroelasticity testing. Figures 3 and 4 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 in the following sections.

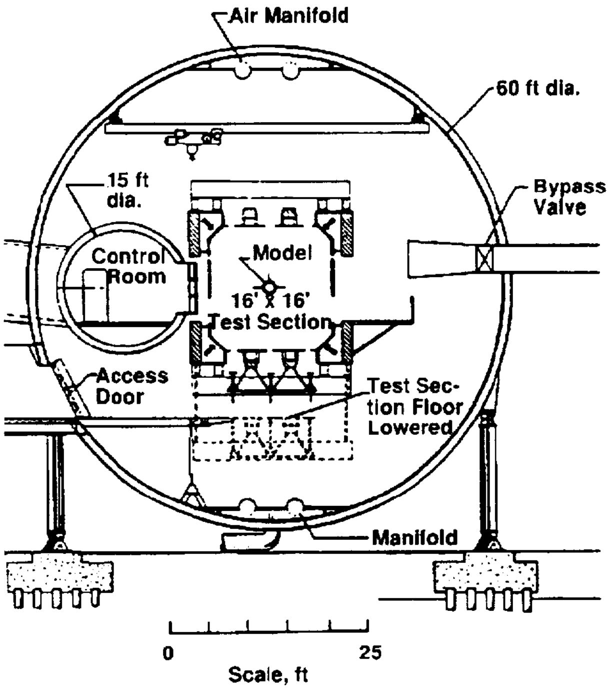


Fig. 4- Cutaway view of test section area of TDT.

Special Facility Features

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 return leg of the wind-tunnel circuit (see Fig. 3). In the event of a model instability, such as wing flutter, these quick-actuating bypass valves can be opened. This opening causes a rapid reduction in the test section Mach number and dynamic pressure; hopefully resulting in saving 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, with significantly smaller reductions in dynamic pressures at low Mach number conditions. Half of these reductions occur in about three seconds.

Airstream Oscillator System- Another special capability available in the TDT is a set of four oscillating vanes, referred to as the airstream oscillator system. The vanes are located upstream of the test section and can be driven sinusoidally to simulate atmospheric turbulence or gusts. These vanes have been used in a number of tests for the purpose of gust loads studies and active gust load alleviation demonstrations. Reference 11 contains a good description of the TDT airstream oscillator system, and references 12 and 13 describe two different experimental studies conducted using the airstream oscillator system.

Control Room- Another convenient feature of the TDT is that the control room, from which the tunnel is operated and from which the wind-tunnel test is directed, is physically situated directly adjacent to the test section within the pressure shell of the test chamber plenum (see Figs. 3 and 4). The control room has a large matrix of observation windows so that direct visual observation of the wind-tunnel model is possible. This feature has proven to be very valuable because of the dynamic nature of aeroelastic testing and because constant visual monitoring is essential to the success of testing. Also, 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.

Test Section Isolation- 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. With the isolation valves closed, only about 25 percent of the test medium in the entire tunnel circuit has to be processed to allow access to the wind-tunnel model.

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 of a model failure that could damage the facility fan blades is fairly high. 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.

Cooling Coils- A final feature of the TDT that contributes to the ability to complete successful aeroelastic studies is the ability to regulate the airstream temperature in the TDT. A set of cooling coils is located internal to the test circuit at the turning vanes immediately downstream of the drive motor for the purpose of maintaining a reasonably constant operating temperature in the facility during testing. 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 rise to an extreme of about 140° F at the highest operating dynamic pressures, which require the most drive motor power to achieve. The ability to control operating temperatures is important because the material stiffnesses of the types of materials that must be used in order to build aeroelastically scaled models are sometimes quite sensitive to temperatures.

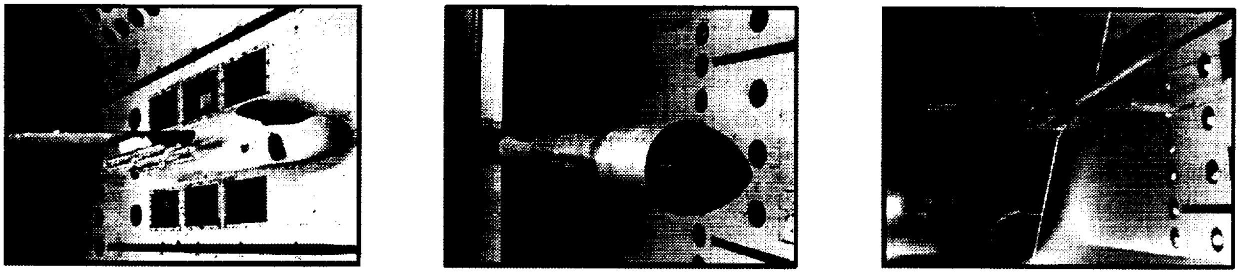
Testing Abilities

As previously stated, the TDT has been used to conduct many types of tests on many types of vehicles for almost four decades. Tests have included flutter, divergence, buffet, gust loads, rotorcraft aeroelasticity and loads, unsteady pressure measurements, ground wind loads, dynamic response, atmospheric reentry loads and dynamics, propeller-whirl flutter, stall flutter, aileron reversal, control surface buzz, flight stability, stores flutter, fuel-slosh dynamics, active structural mode control, maneuver load control, active buffet alleviation, active and passive flutter suppression, and many others. Vehicles tested have included general aviation airplanes, commercial transports, military fighters, rotorcraft, tiltrotor vehicles, launch vehicles, space shuttle concepts, planetary landers, high-speed civil transports, unmanned high-altitude vehicles and others. In the interest of aeroelastic research many tests have been conducted on non-vehicle-specific models. In general, the special scaling relationships provided with the heavy gas testing capability have driven the need to conduct these types of tests in the TDT.

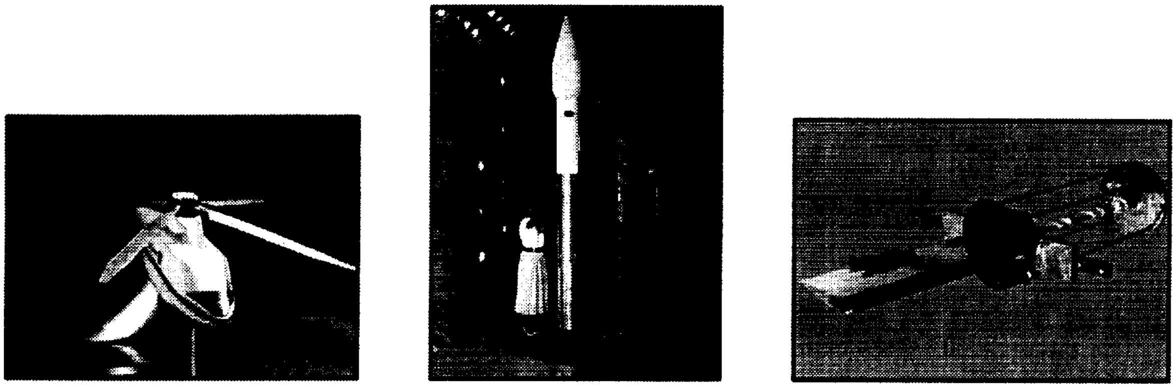
The ability to support and test models in many different configurations has also added to the value of the TDT. Model support systems include sting-supported models, semispan models mounted on a sidewall turntable, "free-flying" cable-mounted models, and floor-mounted models. Figure 5 shows several examples of the different model mounting systems that will be discussed in the remainder of this sub-section.

Semispan models are often tested on the sidewall turntable with half-body fuselage sections which provide appropriate wing root aerodynamics and also remove the wing root area from the boundary layer along the wind-tunnel test section wall. The sidewall turntable mechanism allows models to be tested at various angles of attack which are remotely controlled during testing. Semispan models can also be tested mounted against splitter plates for the purpose of ensuring that the flow over the model is not contaminated by the wind-tunnel wall boundary layer. A special semispan model-mount system that has been widely used for conducting aeroelastic research tests in the TDT is referred to as the Pitch and Plunge Apparatus (PAPA). The PAPA provides for testing rigid aerodynamic surfaces that are mounted to a flexible support system to allow pitch and plunge motions and even classical two-degree-of-freedom flutter. This apparatus assists in the difficult task of determining and separating aerodynamic and structural effects by providing a dynamic support system with a rigid aerodynamic surface. References 14 - 17 describe some results that have been obtained using this PAPA mount system.

A recent addition to the semispan model test capability at the TDT is a retractable sidewall turntable. This turntable is located approximately 2.5 ft downstream of the primary TDT sidewall turntable and is able to move in and out with respect to the sidewall to potentially allow ease of access to certain areas of the wind-tunnel model systems, as well as to allow for the installation of systems such as the PAPA mount system or force-and-moment balances beyond the plane of the test section sidewall.



Sidewall Turntable Sting Two-Cable System



Rotor Testbed Floor Turntable Pitch and Plunge Apparatus

Fig. 5- Model mounting systems for the TDT

Two primary floor mount systems are frequently used in the TDT. A large, removable floor turntable can be used in the TDT. This turntable is generally used for the testing of ground wind loads models, most often of launch vehicles on the launch pad, to provide a mechanism for changing the wind azimuth angle of the freestream flow over the model. The second primary floor mount system is the Aeroelastic Rotor Experimental System (ARES) that is used for rotorcraft aeroelasticity and loads testing of rotor and rotor-hub systems.

In addition to floor mounts, full-span models can be tested in the TDT on a test-section centerline sting support apparatus. This apparatus provides for vertical translation of models in the test section, which is generally more important during model setup or configuration changes than during actual testing. More importantly, the sting apparatus also allows for the remote positioning of model angles of attack, within approximately a ±23° range of motion. This range can also be extended by the use of 5°- and 10°-offset sting sections that are readily available at the TDT facility.

The final primary support technique used in the TDT is a cable-mount model support system. Fig. 5 shows an F/A-18 E/F aeroelastically scaled model mounted on a two-cable support system typical of current test set-ups. For configurations in which the interaction of fuselage flexibilities, flight stability modes, and aeroelastic modes are important, the cable-mount system enables this interaction to be simulated in the tunnel.

R-134a Properties

One of the difficulties in dealing with R-134a as a test medium in the TDT is the necessity to account for gas properties under the recognition that a small fraction of the test medium will always be air. Equations are being developed that estimate flow properties for the appropriate mixture of R-134a and air. In order to accomplish this, thermodynamic properties of the gas must be calculated as a function of static pressure, static temperature, and gas purity. It is not the intention of this paper to give a thorough explanation of the required mixture equations; however, in order to give the reader some feel for what goes into calculating R-134a flow properties, the following discussion will address gas properties for pure R-134a. The molecular weight of R-134a, as shown in Table 1, is

$$M_g = 102.03 \text{ kg/kmol} .$$

Therefore, the gas constant for R-134a is

$$R = \frac{\bar{R}}{M_g} = \frac{8.314\frac{\text{kJ}}{\text{kmol}\cdot\text{K}}}{102.03\frac{\text{kg}}{\text{kmol}}} = 0.0815\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

$$= 487.3\frac{\text{ft}^2}{\text{sec}^2\cdot\text{R}}$$

Under ideal gas assumptions, the constant-pressure heat capacity coefficient is given by:

$$\mathrm{C_p} = 0.3437 + (3.988 \times 10^{-4})\mathrm{T} - (2.113 \times 10^{-7})\mathrm{T}^2 + (7.295 \times 10^{-11})\mathrm{T}^3 \; \frac{\mathrm{Btu}}{\mathrm{lb \cdot R}}$$

and the constant-volume heat capacity coefficient is given by:

$$\mathrm{C_v} = 0.7540 - (2.199 \times 10^{-3})\mathrm{T} + (3.211 \times 10^{-6})\mathrm{T}^2 - (1.539 \times 10^{-9})\mathrm{T}^3 - \frac{2.341 \times 10^4}{\mathrm{T}^2} \; \frac{\mathrm{Btu}}{\mathrm{lb \cdot R}}$$

For nearly pure R-134a at T=530 R (~70° F), this leads to a ratio of specific heats of

$$\gamma = \frac{\mathrm{C_p}}{\mathrm{C_v}} = 1.13 \; .$$

In comparison, the ratio of specific heats for air is approximately $\gamma = 1.4$ and for the previous heavy gas, R-12, $\gamma \approx 1.14$. Under the assumptions of nearly pure R-134a and that R-134a is an ideal gas, the speed of sound in R-134a is

$$a = \sqrt{\gamma R T} = 540 \text{ ft/sec} \; .$$

From this point, all flow parameters for pure R-134a can be calculated using compressible flow equations.

Table 1 shows a comparison of several properties of the operating gases discussed herein. As can be seen, compared to the properties of air, R-134a has properties relatively close to the previous operating test medium of R-12. The fairly large change in gas properties between the heavy gases and air results in a number of advantages in terms of facility operations and capabilities. In the heavy gas, the TDT can achieve higher densities and, therefore, higher dynamic pressures for the same Mach number. In R-134a at a fixed Mach number, approximately a 100 percent increase in dynamic pressure can be achieved as compared to air operations. Other parameters are likewise affected. For instance, significantly higher Reynolds numbers can be achieved due to the changes in gas density, velocity (speed of sound), and kinematic viscosity. In addition to these improved operating capabilities, the heavy gas allows for many advantages in aeroelastic model scaling.

Scaling Relationships

In order to properly interpret wind-tunnel results with regard to a flight vehicle, it is necessary to account for scale effects. The effects of different phenomena generally require different scaling considerations. For instance it is well known that Reynolds number simulation is often of prime importance in simulating the proper aerodynamic flow field. Much effort has been directed toward proper representation of full-scale Reynolds number. One example being the National Transonic Facility at NASA Langley which was designed and built primarily for the purpose of full-scale Reynolds number simulation through the combination of testing at high pressures and at cryogenic temperatures. In a similar fashion, the Langley TDT was designed and built to allow for the proper simulation of parameters that are important in the field of aeroelasticity.

The following discussion will detail the essential scaling parameters associated with an aeroelastic model, such as a flutter clearance model, in an attempt to explain the advantages that the TDT offers for aeroelastic testing with regard to scaling. This discussion is not an attempt to thoroughly explain the various implications of all aspects of scaling parameters and their impact on the usefulness of aeroelastic measurements. Reference 18 contains a good description of scaling considerations in designing dynamically scaled wind-tunnel models.

One of the first scaling parameters that must be considered, and perhaps the easiest to handle, is a geometric length scale. This is primarily driven by the facility size. From the standpoint of building an aeroelastic model that properly simulates structural elasticity, it is generally advantageous to build as large a model as possible. However, this maximum size is constrained by wall interference and shock reflection considerations and, in a few cases, by the streamwise region of good flow within the test section. In general, a wind-tunnel model designed for testing in the TDT is limited to a maximum span of approximately nine feet, whether a semispan or a full-span model. Ref. 19 contains a table of model dimension ratios suitable for use as sizing guides in building models for testing in transonic tunnels such as the TDT.

The other scaling relationships that are of primary importance for aeroelastic scaling are Mach number, frequency, and mass. It is imperative that Mach number be matched in order to properly simulate transonic aerodynamic conditions. The ability to match Mach number requires a facility that can obtain the desired Mach number. In the case of flutter and other aeroelastic phenomena, the Mach numbers of concern are often in the transonic range. The TDT offers the ability to test in the transonic range. The required test velocity to match Mach number is significantly reduced (see speed of sound in Table 1) when using a heavy gas test medium. These reduced velocities require lower facility drive motor speeds (approximately one-half) to achieve a given Mach number condition. This results in reduced tunnel power consumption for a given Mach number-dynamic pressure condition compared to air operations.

A slight limitation of the new heavy gas in the TDT is that it is anticipated that the maximum operating Mach number of the facility will not be quite as high as it was with the previous heavy gas. This limitation is generally viewed as acceptable since the facility will still be able to test beyond the speed of sound so that the most critical flutter condition can be measured for most models. Figure 6 shows the estimated operating boundary in R-134a compared to the previous operating boundary in R-12 and the operating envelope in air.

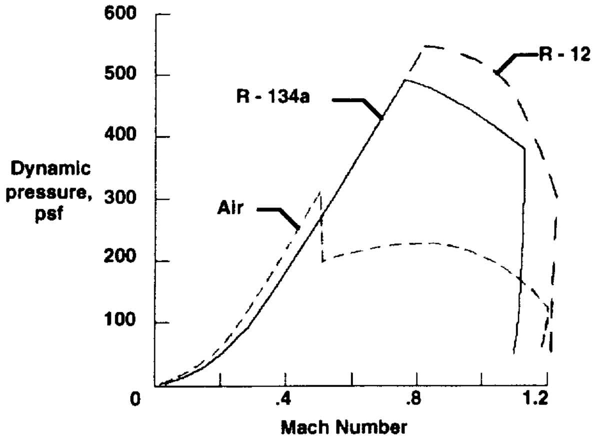


Fig. 6- Operating boundaries in the TDT for three test mediums: air, R-12, and R-134a (R-134a boundary estimated).

The real advantages of the heavy gas properties for an aeroelastic model begin to manifest themselves when one begins to consider scaling the dynamic properties of the vehicle to properly match frequencies. Frequencies are properly scaled when the following relationship is satisfied:

$$\left\{\frac{V}{b\omega}\right\}_W = \left\{\frac{V}{b\omega}\right\}_V$$

Since the length has been previously constrained, primarily by facility size, the ratio of model structural dynamic frequencies to vehicle frequencies is further influenced only by the test medium velocity, which is directly related to the speed of sound at a given Mach number. As shown in Table 1, this means that model frequencies in heavy gas (R-134a) will only be about half the values they would have had to have been in an air test medium. This frequency reduction makes the construction of a model less difficult since it can be less stiff than an appropriately scaled model that would be designed for testing in air at the same flow conditions. Also, with regard to the safety aspects of testing such models, it is easier to observe, and potentially save, a wind-tunnel model if destructive phenomena such as flutter occur at lower frequencies. Lower frequencies affect visual observation abilities as well as data acquisition and monitoring equipment requirements.

The final parameter that is essential for proper scaling of an aeroelastic model is mass:

$$\left\{\frac{m}{\rho b^3}\right\}_W = \left\{\frac{m}{\rho b^3}\right\}_V$$

For this parameter, the increased density of R-134a relative to air at a given temperature and pressure combination allows a properly scaled wind-tunnel model to be built that is approximately four times heavier than would result for air testing. This weight increase eases the difficulty of building aeroelastically scaled models because it is very difficult to match stiffness and meet strength requirements on a lightweight model.

Other parameters need to be considered when designing models, such as Froude number and Reynolds number. However, some compromise is generally required in order to build and test aeroelastically scaled models. As previously discussed, testing in the heavy gas at the TDT does provide increased Reynolds numbers, although the Reynolds numbers will not generally match flight conditions. Another benefit of using the heavy gas is that in addition to matching the primary aeroelastic scaling parameters, Froude number can also be matched for a model that is approximately one-quarter geometric scale. Froude number scaling can be important because it will ensure proper scaling of static deflections. If subsonic Mach numbers are considered the critical regime for a particular model, then Mach number scaling can be sacrificed and Froude number scaling is considered a more critical parameter.

Calibration Plans

A series of calibration tests have been planned for the TDT to quantify flow properties and flow quality after the completion of the facility conversion to allow operation in R-134a. The current focus of the calibration efforts will be to determine a suitable set of instruments and measurement techniques to ensure that accurate test section flow conditions are being measured. Beyond this, there are also plans to make Mach number distribution measurements in the TDT test section area along the test section walls, along the centerline of the test section, and at a matrix of locations across the test section cross section for several streamwise locations. Additionally, boundary layer thickness will be measured around the test section and at several streamwise locations in the test section. Turbulence and flow angularity measurements will be made at several streamwise locations using a sting-mounted flow survey rake. Finally, an attempt will be made to directly measure the speed of sound of the test medium to potentially improve flow property measurement accuracy for mixtures of heavy gas and air. In addition to these efforts to determine the flow properties in the TDT for both air and R-134a test mediums, another goal of the calibration effort is to determine the maximum operating capabilities of the TDT in terms of dynamic pressure and Mach number. The following subsections will discuss in more detail the objectives and plans for the calibrations efforts.

Primary Tunnel Parameters

The most important aspect of the planned calibration efforts will be to determine proper instrumentation locations to ensure accurate flow property measurements, particularly with the new R-134a heavy gas operating capability. The determination of the primary flow parameters fundamentally requires the measurement of only four properties: stagnation pressure, static pressure, stagnation temperature, and R-134a purity.

Historically at the TDT, stagnation pressure has been measured in the settling chamber (see Fig. 3) of the TDT by a total pressure probe mounted two feet away from the west wall of the settling chamber at a position slightly below the vertical centerline of the settling chamber. During the new calibration effort, stagnation pressure probes will be mounted at nine different locations several feet downstream of the tunnel turning vanes (located just upstream of the settling chamber). Measurements will be made at these new probe locations, as well as the previous location, primarily to determine if the original probe provides a sufficiently representative measurement of stagnation pressure or if a new measurement location or technique, such as averaging several probes, may be needed in future testing.

The primary static pressure measurement has historically been made via a tube located between the west wall of the plenum chamber and the control room, again near the vertical centerline of the tunnel circuit. This appears to be a reasonable location under the assumption that the test medium in the plenum is relatively still and at nominally uniform pressure except in the immediate vicinity of the sidewall slots in the test section. In order to check on the accuracy of the existing static pressure measurement, a number of tubes will be located at various positions in the plenum during the calibrations to assess static pressure measurement as a function of location in the plenum.

In the past, stagnation temperature has been measured with thermocouples in the TDT. This measurement was made just a few feet downstream of the cooling coils in the tunnel circuit (see Fig. 3). As with stagnation pressure and static pressure, a number of thermocouples will be used during the calibration effort to determine the most appropriate location for measuring the facility stagnation temperature. It is anticipated that a measurement in the settling chamber may become the primary stagnation temperature measurement location in the future. The previous arrangement may have placed the thermocouple too close to the facility cooling coils, not allowing sufficient mixing before reaching the measuring instrument.

The final parameter needed to calculate all pertinent flow properties is the purity of the R-134a gas with respect to air contamination. It is possible to eliminate the need to directly measure gas purity if the speed of sound of the test medium mixture can be measured under the assumption that the mixture is of two thermally perfect gases for which the individual gas properties are known. This possibility will be discussed in more detail in a later section. Previously, flow properties in the TDT were calculated for the R-12 heavy gas medium based on purity measurements made with gas analyzers. This technique will still be the primary technique, but will employ a new system of modern gas analyzers for the new heavy gas.

Mach Number Distributions

An important aspect of calibrating the TDT will be to measure static pressure variations as a function of position in the test section. In general, these test section static pressures will then be converted to local Mach numbers based on the settling chamber stagnation pressure and stagnation temperature and, in the case of R-134a heavy gas testing, test medium purity. Under the assumptions that the ratio of specific heats is available based on the test section purity (using real gas mixture equations) and that ideal gas flow equations are sufficiently accurate, the local Mach number will then be calculated based on the equation

$$M_l = \sqrt{\left\{ \frac{2}{\gamma - 1} \left[\left(\frac{p_o}{p_l} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right] \right\}}$$

Mach number distribution measurements will be made in three general categories summarized in the following subsections. The ultimate goals of these local static pressure measurements (and calculated local Mach numbers) are to determine if there are significant variations in Mach number through the test section and to determine if corrections to the measurement of test section Mach number are required.

__Sidewall Pressure Measurements__- The term sidewall pressure measurements is being used here to describe any measurement of local static pressure along any of the primary wall, ceiling, or floor surfaces of the TDT test section. Four primary streamwise rows of static pressure ports will be located in the test section, one row on each of the primary test section surfaces. There will be approximately 28 static pressure ports along each of these rows. Fig. 7 shows a conceptual drawing of the placement of these static pressure port rows in the TDT test section. The static ports will be spaced more densely in the vicinity of the sidewall turntable, where sting-, cable-, and sidewall-mounted models are tested.

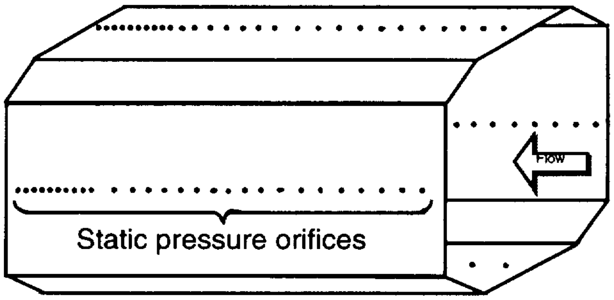


Fig. 7- Conceptual drawing showing approximate locations of sidewall pressure orifices.

__Centerline Tube Measurements__- To enable the measurement of static pressures along the centerline of the TDT test section, a new centerline tube apparatus is being fabricated. A conceptual drawing of the placement of the centerline tube is shown in Fig 8. This apparatus will attach to the TDT sting support and extend forward through the test section into the aft region of the settling chamber. Positioning the nose of this centerline tube in the lower flow speeds of the settling chamber will minimize wake disturbances that could cause erroneous static pressure measurements downstream along the centerline tube. The tube will have static pressure ports at approximately 127 streamwise positions. The centerline tube will also have an orifice for measuring stagnation pressure at the nose of the tube in the settling chamber. This will serve as an additional stagnation pressure measurement to assist in determining the best technique with which to measure the primary flow stagnation pressure.

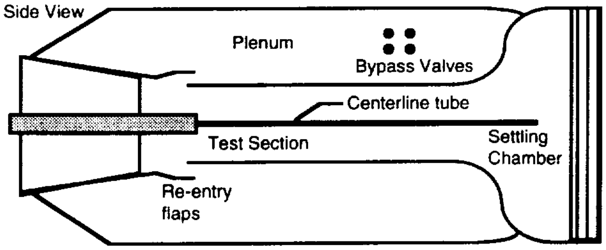


Fig. 8- Sketch of centerline tube in TDT test section.

Survey Rake Measurements- The final apparatus that will serve as a measurement of local Mach number in the test section will be a flow survey rake that will be sting mounted in the test section. Figure 9 is a conceptual drawing illustrating the positioning of this survey rake. This rake will be a single horizontal blade with eleven probes on the leading edge. Several probe devices will be available for use on this flow survey rake. The pertinent devices with regard to the measurement of local Mach number will be static and stagnation pressure probes. By mounting these probes at the various positions across the rake, the Mach number distribution of the central span of the test section can be determined. The probes on the rake will span approximately five feet on either side of the test section centerline. In addition to this spanwise measurement of local Mach number, the rake will be able to traverse on the sting to determine the vertical distribution of Mach number in the test section.

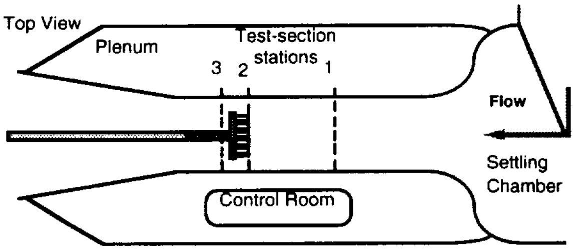


Fig. 9- Drawing representing survey rake device. Three positions for locating the survey rake are also shown by dashed lines and numbers.

The survey rake will have the capability of being installed at three different streamwise positions in the test section (alternative positions indicated in Fig. 9). Position 1 will be at the test section station position corresponding to the center of the hub location for the ARES rotorcraft testbed that is often used in the TDT to conduct rotor aeroelastic and loads research. Position 2 will be at the streamwise location of the pitch axis of sidewall semispan models, 10 ft downstream of position 1. Position 3 will be 3 ft further downstream where the retractable turntable is currently positioned. Position 3 measurements will provide information regarding the streamwise variation of Mach number in the test region around the primary model mount positions for sting, cable and sidewall mounts and are very useful particularly since swept-wing models will actually cover a range of test section stations.

Boundary Layer Measurements

To assess the possible influence of proximity of a model to a test section sidewall, a series of boundary layer rakes are being fabricated for use at up to six positions around the test section perimeter simultaneously. These rakes will extend from the sidewall surface approximately one foot into the flow. The boundary layer rakes will have numerous stagnation pressure tubes along their span to give the variation in stagnation pressure from the wind-tunnel wall out into the freestream flow. Figure 10 shows an approximate layout of the stagnation pressure tubes along the boundary layer rake. In addition to the positioning of these probes around the inside perimeter of the test section, the six probes (or subsets thereof) can also be moved to other streamwise positions to allow the measurement of streamwise variation in boundary layer characteristics.

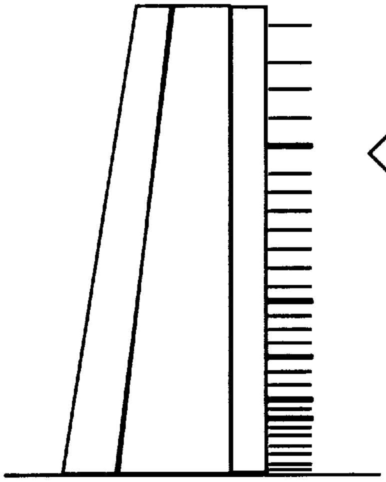


Fig. 10- Boundary layer rake drawing.

Turbulence Measurements

Turbulence levels in the TDT will also be measured during this calibration program. Turbulence information is considered very important, particularly when dynamic response is of prime interest and may be highly influenced by background turbulence levels. To make an assessment of turbulence in the TDT, a number of hot-wire probes will be available for testing on the sting-mounted survey rake.

Speed Of Sound Measurements

An attempt is currently being made to assemble a system of acoustic transmitters and receivers that could potentially measure the speed of sound of the test medium. Figure 11 is a conceptual drawing showing a general idea of how the transmitters and receivers could be located in the test section or the test section plenum area. From the speed of sound, the proportion of the gas constituents can be determined given the known properties of pure R-134a and air, and from these purity proportions and other measured tunnel conditions, all other flow properties can be calculated. The proportion of gases is calculated based on the following equation,

$$a_x = a_h \sqrt{\frac{x\left(\frac{\gamma_a}{\gamma_h} - 1\right) + (1 - \gamma_a)}{\left[1 + x\left(\frac{Mg_a}{Mg_h} - 1\right)\right]\left[x(\gamma_a - \gamma_h) + (1 - \gamma_a)\right]}}$$

as given in reference 20. Such a speed of sound measurement system has the potential for improving the accuracy of R-134a property calculations, although it remains to be determined if the most accurate process will be the direct measurement of test medium purity via new gas analyzers or through the direct measurement of the speed of sound.

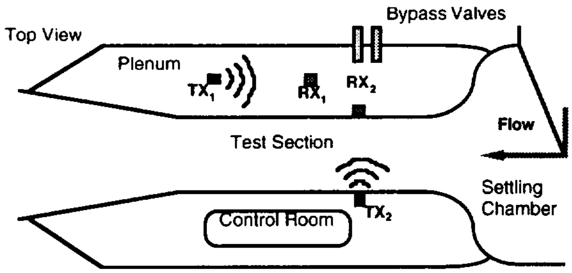


Fig. 11- Conceptual drawing of possible arrangements of equipment for measuring speed of sound.

Flow Angularity Measurements

Another important flow characteristic to understand for proper testing in a wind-tunnel facility is flow angularity. A fourth set of probes will be available for mounting on the survey rake that will allow the measurement of flow angles with respect to both the horizontal and vertical planes of the test section. The probes that will be used for the purpose of flow angularity measurement are generally referred to in the literature as five-hole probes.

Tunnel Configurations

In addition to the above types of calibration measurements that will be made after the completion of the heavy gas upgrade of the TDT, another important aspect of calibrating the facility will be to account for configuration variables of the facility itself. Aside from drive motor speed, the primary TDT facility variable is the position of the re-entry flaps located on the ceiling and the floor at the downstream end of the test section. These flaps provide for efficient operation of the facility during transonic testing. The re-entry flaps essentially re-capture facility flow that has escaped, or expanded, through the test section sidewall slots. The flow impinges upon the re-entry flaps and is drawn back into the tunnel circuit through the tunnel expansion cone downstream of the test section. A part of the calibration efforts will be to make an assessment of the optimum re-entry flap settings to be used at different Mach number and dynamic pressure combinations to provide the best Mach number distribution through the test section. Recommendations for re-entry flap settings may very well be dependent on the test medium, so that the change over to R-134a as the operating gas may result in changes in the use of the re-entry flaps.

Another facility variable is the position of the pre-rotation vanes that align the flow prior to entering the drive system fan blades for improved facility operating efficiency. The pre-rotation vanes may have an effect on the flow turbulence level and the flow angularity, so measurements will be made for variations in the pre-rotation vane settings. However, the effect of the pre-rotation vanes setting is probably more of an issue in determining maximum operating conditions of the facility, particularly with the new test medium, than in determining effects on the flow properties in the test section.

Another tunnel variable that will be considered for its effect on flow properties will be sidewall slots on the wall of the test section where semispan models are typically tested. For most tests conducted in the TDT, the effect of the proximity of the test article to the test section sidewall slots has been considered minimal because most aeroelastic models are tested at nearly zero-lift conditions. Also, most often the important lift loads for aeroelastic testing are dynamic in nature and therefore the proximity of the sidewall slots may not be as important as they would be for large, steady aerodynamic loads. However, the possible influence of the sidewall slots has led to a decision to conduct facility calibrations, particularly for the new heavy gas R-134a, with these sidewall slots opened and closed.

Typical TDT Tests

After the completion of the calibrations, the TDT will return to operational status with the capability of testing in either air or the new R-134a heavy gas test medium. The new R-134a test medium capability will be beneficial to the aeroelastic testing community, supporting aircraft vehicle programs and aeroelastic research developments for many years to come. In an attempt to emphasize the potential future impact of TDT testing capabilities, the following sub-sections summarize several key recent TDT wind-tunnel test programs completed prior to the conversion to the R-134a testing capability. These four programs cover a broad range of aeroelastic vehicle-development and research objectives and represent the wide range of vehicle types that are typically studied in the TDT.

F/A-18 E/F

A series of five wind-tunnel test entries was completed in the TDT for the purpose of flutter clearance of the new F/A-18 E/F fighter. The wind-tunnel model is shown in the cable-mount configuration in Fig. 12. In many ways this test series represents a typical flutter clearance program that might be conducted in the TDT for a military aircraft. The tests consisted of multiple entries that built upon one another. Model flying stability was first verified on the cable-mount system with a "rigid" version of the model. The second goal of the test series was to verify the aeroelastic characteristics of the individual surface components on a sting mount to minimize the risk of catastrophic loss of the whole model. Following the components testing, the entire flexible vehicle was flutter cleared on the cable-mount system: first in a clean-wing configuration followed by stores-clearance testing of many store configurations.

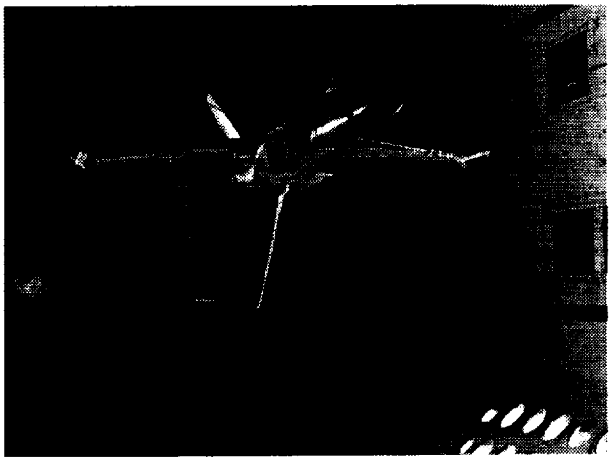


Fig. 12- F/A-18 E/F model cable-mounted in the TDT.

Flutter Suppression Using Piezoelectric Actuators

Experimental aeroelasticity research programs, often not directly associated with any specific flight vehicle, are frequently carried out in the TDT. One such base research program involved the design and fabrication of a model that was fitted with many piezoelectric elements that could be used to induce strain in the structure of the wing model. Through the use of active control, these piezoelectric elements were employed to suppress flutter and reduce loads. Figure 13 is a photograph of the wing with the aerodynamic-geometry shells removed to expose the piezoelectric elements. Control laws tested in this program resulted in as much as 12.5 percent increases in the flutter dynamic pressure. This testing proved that piezoelectric control of dynamic instabilities is possible. Reference 21 summarizes some of the results from this test program.

Tiltrotor Research

As previously indicated in this paper, the TDT is often used for conducting rotorcraft tests. In recent years, a number of research studies have been completed associated with a tiltrotor model testbed. Figure 14 shows a photograph of this testbed, called the Wing and Rotor Aeroelastic Testing System (WRATS). Through the WRATS test program the following objectives have been successfully demonstrated: tiltrotor vibratory loads have been reduced using active swashplate/flaperon controls and composite tailoring of the wing structure has been shown to improve propeller whirl flutter instability margins. A recent summary of the active vibratory loads reduction as well as a description of the WRATS testbed is available in reference 22.

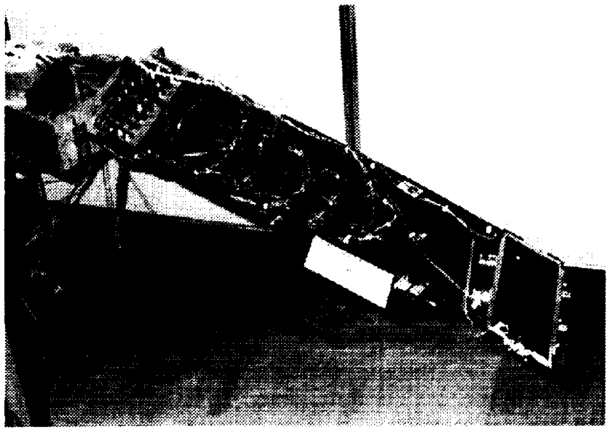


Fig. 13- Model with aerodynamic shell sections removed to show piezoelectric actuators.

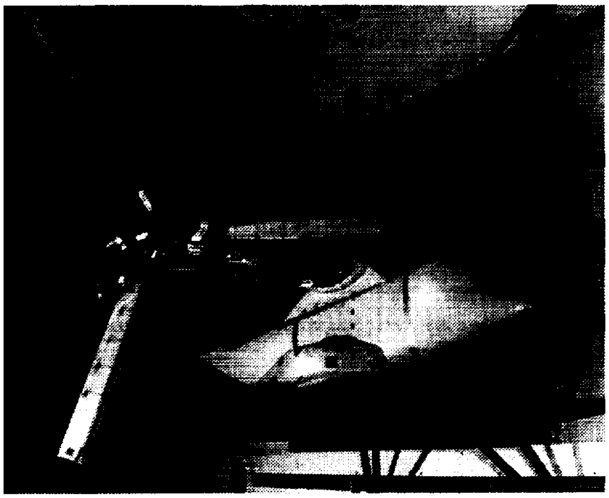


Fig. 14- WRATS tiltrotor model mounted against a splitter plate in the TDT.

Launch Vehicles

A number of launch vehicle tests have also been conducted in the TDT in recent years. These tests include a ground wind loads test of the Atlas-Centaur II vehicle and three tests primarily concerned with the buffet response over hammerhead payload configurations in the transonic flight regime, one test for each of the following launch vehicles: the Atlas-Centaur I Large Payload Fairing, the Delta II Composite Payload Fairing, and the Delta III. Reference 23 summarizes the TDT test results for the Atlas-I wind-tunnel model. A photograph of the Delta III launch vehicle model is shown in figure 15. These tests proved to be significant risk mitigation steps in verifying the flight readiness of the vehicle designs with regard to many dynamic aeroelastic concerns.

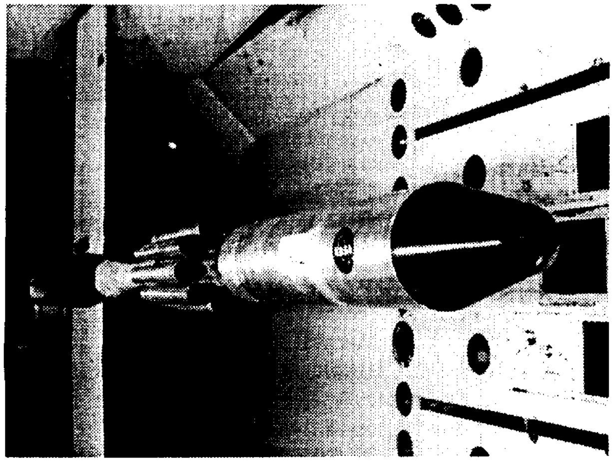


Fig. 15- Photograph of Delta III launch vehicle model sting-mounted in the TDT.

Concluding Remarks

The NASA Langley Transonic Dynamics Tunnel (TDT) was designed and built for the specific purpose of aeroelasticity research. Over the years it has been maintained and modified to allow for continued relevant contributions to the advancement of the fundamental understanding of aeroelastic phenomena. Most major United States commercial transports and military aircraft which are capable of flight at transonic speeds have been tested at the TDT at some point in their design or development phases. The TDT provides unique capabilities through the combination of large scale, high speed, high density, and variable pressure that make the facility ideally suited for testing aeroelastically scaled clearance models. The high density capability is perhaps the most significant feature of the TDT that makes the facility very suitable for aeroelastic testing. This capability was historically provided through the use of the heavy gas R-12 as the test medium. However, recent environmental concerns have led to discontinuing the use of the former heavy gas. To retain its unique capabilities, the TDT is currently being modified to use a new heavy gas, known as R-134a. With R-134a, the TDT will continue to be a viable test facility for the purpose of leading edge aeroelasticity research and dynamic vehicle clearance testing well into the 21st century. The benefits of R-134a as a test medium have been discussed in this paper, calibration plans have been summarized, and several past test programs have been reviewed that show the potential benefits of R-134a heavy gas testing.

References

1. Bisplinghoff, Raymond L.; Ashley, Holt; and Halfman, Robert L.: Aeroelasticity. Addison-Wesley Publishing Company, 1955.

2. Scanlan, Robert H.; and Rosenbaum, Robert: Aircraft Vibration and Flutter. Dover Publications, Inc., 1968.

3. Dowell, Earl H.; Crawley, Edward F.; Curtiss, Howard C., Jr.; Peters, David A.; Scanlan, Robert H.; and Sisto, Fernando. A Modern Course in Aeroelasticity. Kluwer Academic Publishers, 1995.

4. Garrick, I. E.; and Reed, Wilmer H., III: Historical Development of Aircraft Flutter. AIAA 81-0491R, Journal of Aircraft, Vol. 18, No. 11, November 1981.

5. Garrick, I. E.: Aeroelasticity -- Frontiers and Beyond. Journal of Aircraft, Vol. 13, No. 9, September 1976.

6. Baals, Donald D.; and Corliss, William R.: Wind Tunnels of NASA. NASA SP-440, 1981.

7. Moxey, R. L.: Transonic Dynamics Wind Tunnel. Compressed Air Magazine, Vol. 68, Number 10, October 1963.

8. Reed, Wilmer H.: Aeroelasticity Matters: Some Reflections on Two Decades of Testing in the NASA Langley Transonic Dynamics Tunnel. NASA TM-83210, 1981.

9. Doggett, Robert V., Jr.; and Cazier, F. W., Jr.: Aircraft Aeroelasticity and Structural Dynamics Research at the NASA Langley Research Center-Some Illustrative Results. Presented at the 16th Congress of the International Council of the Aeronautical Sciences (ICAS), Jerusalem, Israel, September 1988.

10. Noll, T.; and Perry, B., III: Activities in Aeroelasticity at NASA Langley Research Center. Paper to be presented at the ASME 4th International Symposium on Fluid-Structure Interactions, Aeroelasticity, and Flow-Induced Vibrations and Noise, Dallas, Texas, November 1997.

11. Gilman, Jean, Jr.; and Bennett, Robert M.: A Wind-Tunnel Technique for Measuring Frequency-Response Functions for Gust Load Analyses. Journal of Aircraft, Vol. 3, No. 6, Nov.-Dec. 1966.

12. Stewart, Eric C.; and Doggett, Robert V., Jr.: Dynamic Wind-Tunnel Tests of an Aeromechanical Gust-Alleviation System Using Several Different Combinations of Control Surfaces. NASA TM 78638, March 1978.

13. Redd, L. Tracy; Hanson, Perry W.; and Wynne, Eleanor C.: Evaluation of a Wind-Tunnel Gust Response Technique Including Correlations With Analytical and Flight Test Results. NASA TP 1501, November, 1979.

14. Rivera, José A., Jr.; Dansberry, Bryan, E.; Bennett, Robert M.; Durham, Michael H.; and Silva, Walter A.: NACA 0012 Benchmark Model

Experimental Flutter Results With Unsteady Pressure Distributions. NASA TM 107581, March 1992.

15. Rivera, José A., Jr.; Dansberry, Bryan, E.; Durham, Michael H.; Bennett, Robert M.; and Silva, Walter A.: Pressure Measurements on a Rectangular Wing With a NACA 0012 Airfoil During Conventional Flutter. NASA TM 104211, July 1992.

16. Dansberry, Bryan, E.; Durham, Michael H.; Bennett, Robert M.; Rivera, José A., Jr.; Silva, Walter A.; Wieseman, Carol D.; and Turnock, David L.: Experimental Unsteady Pressures at Flutter on the Supercritical Wing Benchmark Model. AIAA Paper No. 93-1592. Presented at the 34th Structures, Structural Dynamics, and Materials Conference, LaJolla, CA, April 19-22, 1993.

17. Dansberry, Bryan, E.; Durham, Michael H.; Bennett, Robert M.; Turnock, David L.; Silva, Walter A.; and Rivera, José A., Jr.: Physical Properties of the Benchmark Models Program Supercritical Wing. NASA TM 4457, September 1993.

18. Regier, Arthur A.: The Use of Scaled Dynamic Models in Several Aerospace Vehicle Studies. Presented at the ASME Colloquium on Use of Models and Scaling in Simulation of Shock and Vibration, Philadelphia, Pennsylvania, November 19, 1963.

19. Ruhlin, Charles L.; Destuynder, Roger M.; and Gregory, Richard A.: Some Tunnel-Wall Effects on Transonic Flutter. Journal of Aircraft, Vol. 12, No. 3, March 1975.

20. Pozniak, O. M.: Investigation Into the Use of Freon 12 as a Working Medium in a High-Speed Wind-Tunnel. CoA Note No. 72, The College of Aeronautics, Cranfield, United Kingdom, November 1957.

21. McGowan, Anna-Maria R.; Heeg, Jennifer; and Lake, Renee C.: Results of Wind-Tunnel Testing From the Piezoelectric Aeroelastic Response Tailoring Investigation. AIAA-96-1511. Presented at the 37th Structures, Structural Dynamics, and Materials Conference, Salt Lake City, UT, April 15-17, 1996.

22. Nixon, M. W.; Kvaternik, R. G.; and Settle, T. B.: Tiltrotor Vibration Reduction Through Higher Harmonic Control. Presented at the American Helicopter Society 53rd Annual Forum, Virginia Beach, VA, April 29-May 1, 1997.

23. Cole, Stanley R.; and Henning, Thomas L.: Buffet Response of a Hammerhead Launch Vehicle Wind-Tunnel Model. Journal of Spacecraft and Rockets, Vol. 29, No. 3, May-June 1992.