Advanced Capabilities for Wind Tunnel Testing in the 21st Century

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Abstract

Wind tunnel testing methods and test technologies for the 21st century using advanced capabilities are presented. These capabilities are necessary to capture more accurate and high-quality test results by eliminating the uncertainties in testing and to facilitate verification of computational tools for design. This paper discusses near-term developments underway in ground testing capabilities, which will enhance the quality of information of both the test article and airstream flow details. Also discussed is a selection of new capability investments that have been made to accommodate such developments. Examples include advanced experimental methods for measuring the test gas itself; using efficient experiment methodologies, including quality assurance strategies within the test; and increasing test result information density by using extensive optical visualization together with computed flow field results. These points could be made for both major investments in existing tunnel capabilities or for entirely new capabilities.

Nomenclature

CFD	=	Computational Fluid Dynamics
DP-CARS	=	Dual-Pump Coherent Anti-Stokes Raman Scattering
LaRC	=	Langley Research Center
LITA	=	Laser Induced Thermal Acoustics
MDOE	=	Modern Design of Experiment
NASA	=	National Aeronautics and Space Administration
NTF	=	National Transonic Facility
OPO	=	Optical Parametric Oscillator
PLIF	=	Planar Laser Induced Fluorescence
TDT	=	Transonic Dynamics Tunnel
V&V	=	Verification and Validation
ViDI	=	Virtual Diagnostics Interface
UPWT	=	Unitary Plan Wind Tunnel

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I. Introduction

The majority of the ground test facilities in this country were built 40 to 60 years ago; the newest ones are at least 25 years old. Many of these facilities have had testing technology upgrades many times during the intervening decades and, fortunately, most have had their fundamental instrumentation systems completely replaced. Several of these are NASA Langley's most critical testing facilities; for example, the 8-Ft. High Temperature Tunnel started off as a Structures tunnel in 1964 for testing thermal protection systems. The tunnel underwent several modifications over the years, mainly for oxygen enrichment of the flow to allow scramjet testing in the 1980s. These upgrades, described in Ref. 1, allowed the tunnel to complete a series of fueled scramjet tests, leading to the successful Mach 7 X-43A flight in 2004. Following the tremendous success of the X43A, the 8-Ft. High Temperature Tunnel was utilized for testing the Office of Naval Research/DARPA HyFly Dual Combustor Ramjet engine at simulated Mach 4, 5, and 7 conditions. The facility has most recently been used to test both the NASA X43C hydrocarbon fueled engine and the Air Force Research Laboratory X51A engine.[2] The X51A program conducted two highly successful test series for the X51A engine; the last test served as the flight clearance test for the program. The flight test of the X51A vehicle is currently scheduled for January 2010. The flight will demonstrate air-breathing hypersonic propulsion for 5 minutes, accelerating the vehicle from Mach 4.6 to just over Mach 6.

There are several critical needs for aeronautical testing that have developed over the last few decades. Accuracy requirements have become much more stringent as aircraft companies strive to achieve the best performance of their products, and since the cost of testing is so high, customers for the facilities now wish to obtain much more from each test entry. Experimental testing is still the best way to determine "off-design" conditions, where analytical tools simply cannot predict performance reliably. Thus, we must ensure that we add capabilities that continue to make the facilities productive well into the 21st century. While all of NASA's aeronautical test facilities are well beyond their original design lifetimes, thoughtful investments in advanced capabilities and testing technologies have kept them useful. Particular attention must be given in terms of the multi-parameter test requirements that are part of today's program requirements to address current and future aircraft performance related technical challenges.

Two pressing questions facing all of those responsible for operating these facilities are: How can we continue to add meaningful measurement capability to these facilities, and what capability upgrades do we make for single- and multi-parameter testing to ensure that these aging facilities will be well suited to fulfill their required missions and remain viable as long as needed in the 21st century? The present paper summarizes advances in computing power needed for advanced computational flow modeling, it highlights a method for a different test execution strategy, and it outlines several advanced testing methods that can allow these facilities to be useful well into the 21st century.

II. Advancing Computational Modeling

Computational modeling has progressed substantially over the last several decades, and computational modeling and simulation is expected to continue progressing at an ever-accelerating pace. These computational tools need to cover flight regimes and flow conditions for which validated tools need to be developed. Also, extremely fast computing power is needed to rapidly execute these runs in a cost effective manner. Since rapid advances and changes are likely to continue forward in many of the areas that influence facility operations in this new century, Langley Research Center has been studying the nature of changes and preparing for the changes that are to come in the 21st century. The initial findings of this study have been published in a white paper by the first author entitled "A Future State for NASA Laboratories, Working in the 21st Century."[3] At the forefront of these findings is the impact computational advances and digital networking will have on every aspect of our lives. This is most commonly referred to as "Moore's Law," which shows that for many decades, transistor density has been doubling every 24 months, as shown in the chart in Fig. 1.

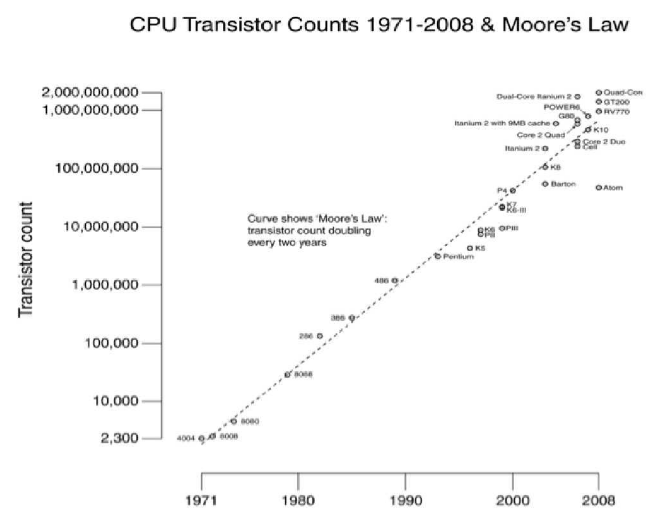

Figure 1. Transistor counts 1971 – 2008 & Moore's Law.

Specifically, Moore's Law[4] describes a long-term trend in the history of computing hardware, in which the number of transistors that can be placed inexpensively on an integrated circuit has doubled approximately every two years. Similar trends are taking place in modeling and simulation, such as computational fluid dynamics (CFD). However, before an experimental capability can be replaced by analytical modeling, the analytical modeling must undergo an orderly process of Verification and Validation (V&V). V&V of simulation tools is a requirement of any computational model before potentially replacing ground test facilities. The process of V&V is expected to have a strong influence on test designs in the next 20 to 40 years. It is expected that this phenomena will continue to progress, mostly through the advances of parallel processing, i.e. packing multiple CPUs into each machine and learning how to effectively use or program them. There are several recent advances in "cluster" computing, or "cloud computing", especially as the price of computers, continues to fall.

III. Advancing Testing Technologies

Since these facilities are expensive to operate and maintain, we need to fully optimize each wind tunnel test to get more out of each run. Thus, we want to study the gas flow, not just the effect on the model. This may be accomplished through the application of a battery of advanced instrumentation such as PLIF, CARS, LITA, Rayleigh, Diode laser absorption, and other off-body flowfield diagnostic techniques. Additionally, advanced data handling and visualization techniques will be required, which will be discussed later in this paper. These technologies help obtain more information from each tunnel run, compared to just looking at traditional forces and moments.

The capabilities required from the wind tunnel in the 21st century will allow the researcher to fully comprehend the physics from a "global" perspective. Traditionally, the vast majority of aerodynamic data has been in the form of scalar point measurements, requiring the researcher to infer the structure and behavior of the accompanying flowfield. Examples include the inferred presence and behavior of discreet features such as vortices or boundary layer transition. However, due to practicality, these measurements are most often made at spatial frequencies far below the Nyquist frequency, and often limited directly to the surface of the model. Through the use of advanced, global measurement techniques, (with multiple techniques used in concert with one another in the same test), both the causes of and effects from such discrete elements of the aerodynamic environment can be catalogued and analyzed. The outcome goes beyond the knowledge of just resultant forces, moments, and pressures to a comprehensive understanding of the inclusive environment in which the test article is fully immersed. This is the *crucial transition* where experimental testing evolves from acquiring data to obtaining knowledge.

The Megahertz (MHz) Nitric Oxide Planer Laser Induced Fluorescence (NO PLIF) instrument is a prime example of how instrumentation has been evolving. Recent work at LaRC employed NO PLIF to obtain both global qualitative and quantitative measurements of the flowfield structure in hypersonic flows. This work illustrates the power of collaboration with universities to advance the capability of a basic tool used for years to understand fluid mechanics, namely, flow visualization. At the heart of this advance is the development of a new laser, capable of pulsing at 1MHz, along with the advancing of imaging capability to capture images at this rate.

This high-speed flow visualization has been demonstrated in a novel test setup by The Ohio State University[5,6,7,8] and the University of Iowa where they used a laser, developed with support from NASA and the Air Force. This NO PLIF imaging system, operating at 1 MHz, is fast enough to resolve unsteady hypersonic flow events such as laminar-to-turbulent transition and separated flows, which is considerably faster than anything available in the past. The primary objective of the project was to develop the MHz rep rate NO PLIF system and to demonstrate it at a NASA facility. The system also incorporates a 1 million-frame/sec camera to image the flow field. These demonstration experiments are in flow fields relevant to the NASA Hypersonics, Space Exploration, and Space Shuttle programs.

Figure 2 shows the pulse-burst laser system that has been developed. A continuous-wave diode-pumped Nd:YAG ring laser serves as the primary oscillator, the output of which is pre-amplified using flashlamp-pumped pulsed amplifiers. The resulting smooth pulse is formed into a "burst" train using a custom "slicer," the output of which is further amplified in a series of six additional flashlamp-pumped amplifiers. The fundamental output at 1.06 microns is converted to second (532 nm) and third (355 nm) harmonic wavelengths using nonlinear optical crystals. The third harmonic is then used as the pump for an injection-seeded Optical Parametric Oscillator (OPO) system, which is mixed with a residual 355 nm pump, creating 100-1000 kHz and 10-20-pulse bursts of tunable output in the vicinity of 226 nm with ~0.15mJ/pulse, which are used for NO PLIF imaging.

Figure 2. A 3'x8' optical table containing The Ohio State University's MHz rate laser system installed next to the 31" Mach 10 tunnel.

The PLIF image sequences are captured using a Princeton Scientific Instruments PSI-IV framing ICCD camera shown in Fig. 3. The camera consists of a pair of sensors, with total available resolution of 160 x 160 pixels. Figure 4 shows an image sequence obtained using the MHz NO PLIF system on a 2-mm tall cylindrical protuberance attached to a flat plate. Flow in the image is from left to right. The laser sheet passes from top to bottom of the image, parallel to the surface of the plate, resulting in a shadow near the bottom left of each image. Laminar flow enters the camera's field of view from the left. The laminar flow transitions to turbulence as it passes by the trip. Individual flow structures (red box) can be tracked and observed as they develop and convect downstream.

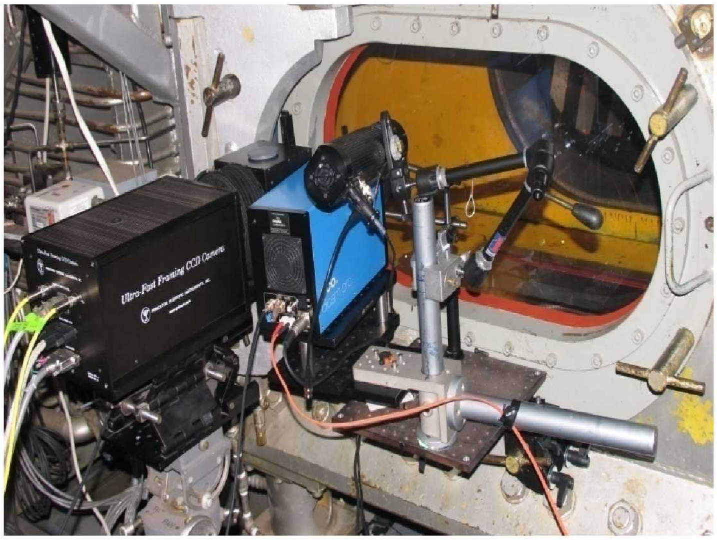

Figure 3. A High Speed Princeton Scientific Instruments PSI-IV system installed next to LaRC's Mach 10 Tunnel (left side of photo).

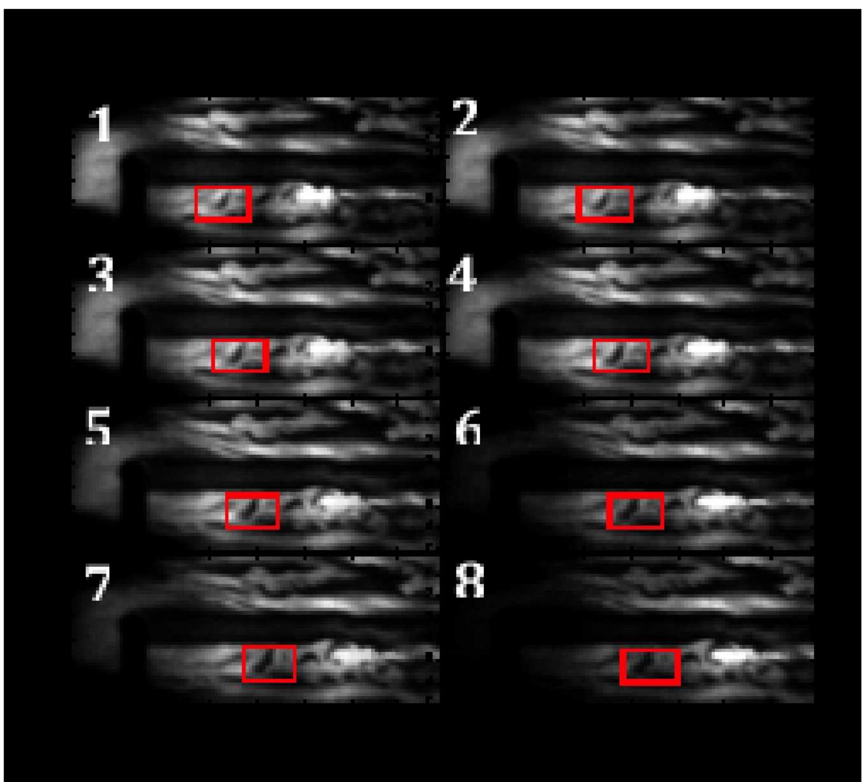

Figure 4. 1 MHz NO PLIF images of flow over a 2-mm tall, 4-mm diameter cylindrical trip attached to a flat plate. Laser sheet is located ~0.7 mm above the 20° flat plate model surface. (From Ref. 8. The flow is from left to right.

Another novel testing technology is Dual-Pump Coherent Anti-Stokes Raman Spectroscopy (DP-CARS). The DP-CARS technique is a nonlinear optical technique in which three laser beams cross, focus, and interact with a gas flow to generate a fourth laser beam that is analyzed to determine the temperature and composition of a flowfield at the crossing point. An important feature of this method is that all the interacting beams are, in fact, spatially coherent laser beams; therefore, the technique can be used to make remote measurements in conditions where there is limited optical access, for example, in ducts through thin slotted windows, such as scramjet engines.

In NASA Langley Research Center's recent use, the three input beams are yellow, green, and red, as illustrated in Fig. 5. The red beam is spectrally broadband, while the yellow and green are spectrally narrow. The combination of the yellow and red beams probe O_2 Raman resonances, while the combination of green and red beams probe N_2 Raman resonances. Both pairs of beams also probe H_2 resonances, and all three beams are required to complete the CARS process. The spectrally broad blue beam then contains information about the concentration of N_2, O_2, and H_2, as well as the temperature from the shape of these spectra.

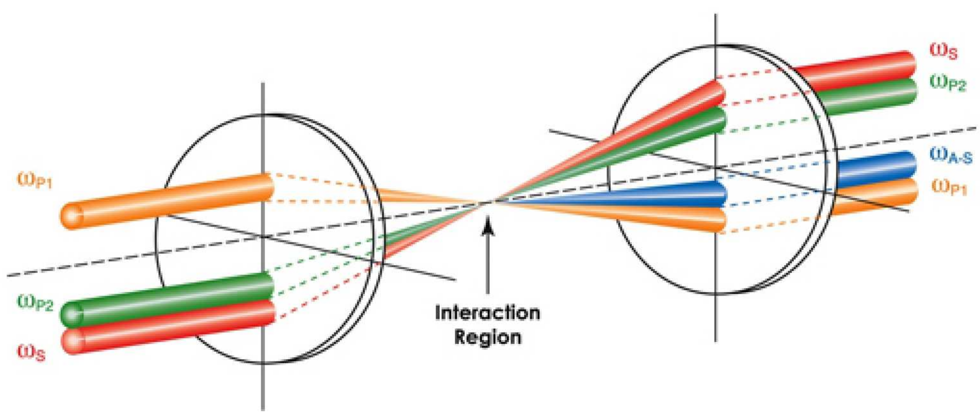

Figure 5: Illustration of the CARS Technique.

Figure 6 shows how DP-CARS mapped the temperature and composition fields in a supersonic combustor.[9] Flow is from top left to bottom right. Hot air enters the duct at the top left, cold H_2 fuel is injected from the top wall, and then burns as the flow propagates downstream, elevating the temperature. These data have been used by several research groups around to world to test and improve their computational methods.

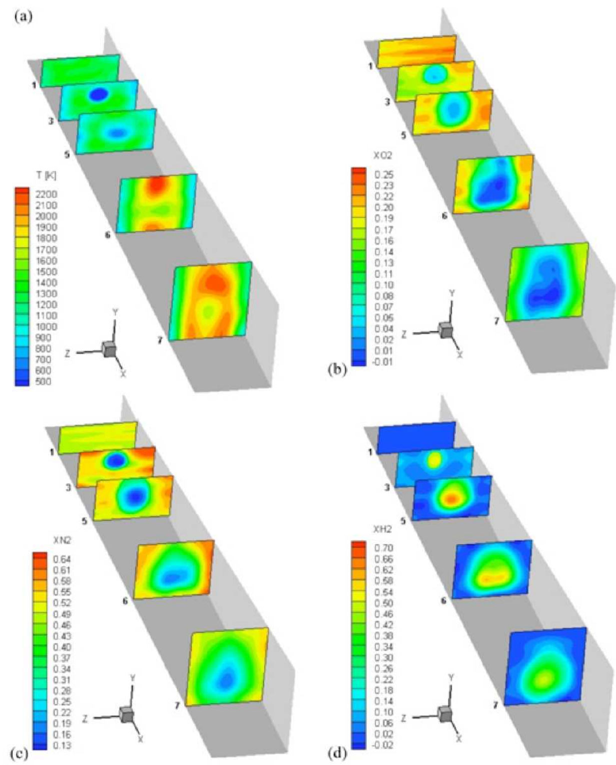

Figure 6: Mean Temperature (a) and Composition fields in a supersonic combustor. The mean O_2, N_2, and H_2 mole fractions are shown in (b), (c), and (d), respectively (from Ref. 9.

It is also expected that technical advances are not limited to the United States, and indeed many other countries have research communities that have been developing technologies. Langley Research Center has recently benefitted from technical advances from international collaborations. For example, the NASA researcher connected with the MHz Optical imaging work has collaborated with researchers from both Australia and Germany.

IV. Advancing Testing Strategies

In addition to advanced test technologies, there are also changes to the process of conducting an experiment, most notably that due to the inclusion of Modern Design of Experiment,[8,9,10,11,12] which represents a revolutionary advancement to the way traditional aeronautical testing has been done. The fundamental advantages of using a Modern Design of Experiment (MDOE) approach is threefold:

1) There is a significant increase in productivity since every single data point contributes to every one of the unknown quantities in which one has interest. This has the benefit that fewer data points are required. (At least 50% fewer data points within the typical test matrices, but it has often been observed that as few as $1/10^{th}$ and up to $1/100^{th}$ of the

originally planned data (using conventional methods) is required). This is done by changing *more* than one factor at a time.

2) An obvious benefit of taking a limited volume of data is that it is now possible to afford the time to integrate quality assurance tactics directly, such as sample replication. A very obvious benefit is that the precision of the measurement is determined during the experiment itself and does not need to rely on claims from the facility, which may be either outdated or exaggerated.

3) A third, but profound, attribute of using an MDOE strategy, is that one optimizes the test matrices for *quality* rather than speed or *quantity*. This is the outcome since one no longer makes run-order decisions based on maximizing data acquisition rate. This often leads to resistance to adopting this method by the aeronautical facility operators, as they have strived for years to obtain the largest volume of data in the least amount of time.

References 7 through 11 cover the essential principles of the MDOE strategy, which must be considered with much more attention to detail, such as what the dependant and independent variables are and how accurately one needs to know them, *BEFORE* coming to the facility. These references provide information and examples of successful applications.

It is essential that facilities be updated and modernized to accommodate MDOE test matrices and testing in virtual presence, or that testing done from a remote location, without the researcher ever having to go to the location of the test facility. Such an investigation would have several issues to overcome before being adopted by the population that has an interest in testing. The first issue is that it would have to be a secure Internet link back to the customer's home site. Mature methods are already available due to the explosive growth evident by Internet applications such as shopping and banking.

V. Advancing Virtual Simulation and Diagnostics

The Virtual Diagnostics Interface, or ViDI, is a methodology of applying two-dimensional image processing, three-dimensional computer graphics, physics-based modeling, and the handling of large data sets toward solving complex aerospace testing and data visualization problems using PC-based workstation hardware. There are three main areas in which ViDI is utilized for ground based testing. These areas are pre-test planning, real-time data visualization in an interactive virtual environment, and post-test data unification, where disparate forms of data are brought together *in-situ* in the virtual environment to help obtain a more global perspective on the causes and relationships of experimental parameters and the resulting physical phenomena reported by the data.[13]

ViDI is a powerful tool for pre-test planning. In a typical scenario, a detailed three-dimensional scale computer model of a test facility, such as a wind tunnel (of which a large library exists), will be merged with the Computer Aided Design (CAD) model of a planned test article. This creates a virtual environment in which the intricacies of the test can be planned out. For example, the required interfacing of the test model and the facility, and any dynamic behavior, such as range of motion, can be explored, altered, and verified, as required. This was done for the

Orion capsule and launch abort system, as shown in Fig. 7. Sting length was analyzed to ensure full range of desired angles of attack without interference from floor or ceiling.

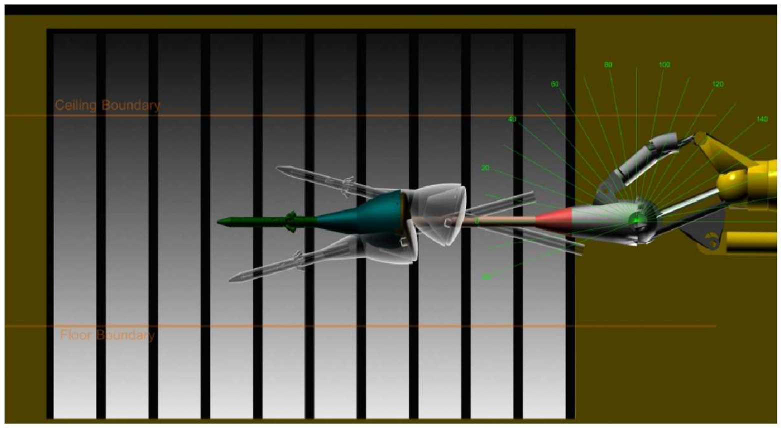

Figure 7. Simulating a test setup in the NASA Langley Unitary Plan Wind Tunnel. Floor and ceiling boundary lines depict limits set to avoid shock wave reflections from affecting the measurements.

Additionally, the user can easily incorporate virtual cameras whose characteristics, such as field of view, pixel resolution, and depth of field, can accurately simulate real cameras. This is a very powerful simulation capability for image-based instrumentation, a rapidly expanding genre of advanced measurement technology.

Through the use of ViDI, all aspects of a test can be simulated prior to entering the facility. This allows the test and research engineers, technicians, and managers to contribute and communicate about the test from a common and accurate reference point. It also allows several what-if scenarios to be explored without the need to tie up costly facility test time. This capability has been utilized for numerous experiments at NASA Langley as well as other NASA and Air Force Research Centers. Figure 8 shows how placement of the two stages was examined. A CFD solution for flow density is depicted for a

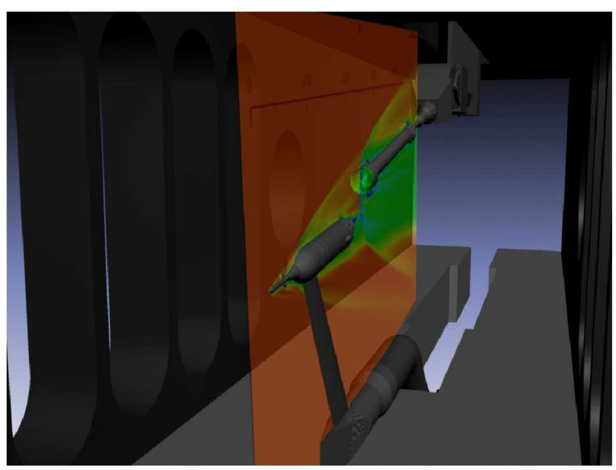

Figure 8. Ares 1 rocket stage seperation test in the Arnold Engineering Development Center Tunnel A. CFD derived flow patterns were included to help depict potential areas where flow features would interact with test support hardware.

given relative displacement of the stages. This simulation allowed reasarchers to understand which portions of the CFD run matrix could be conducted in the facility.

The left side of Fig. 9 is a drawing of the required camera placement to view the scene through a mirror, necessitated by the window lattice structure. In the middle is the ray-traced simulated camera view for the maximum and minimum planned angle of attack settings, and on the right are the actual images from those angle of attack settings.

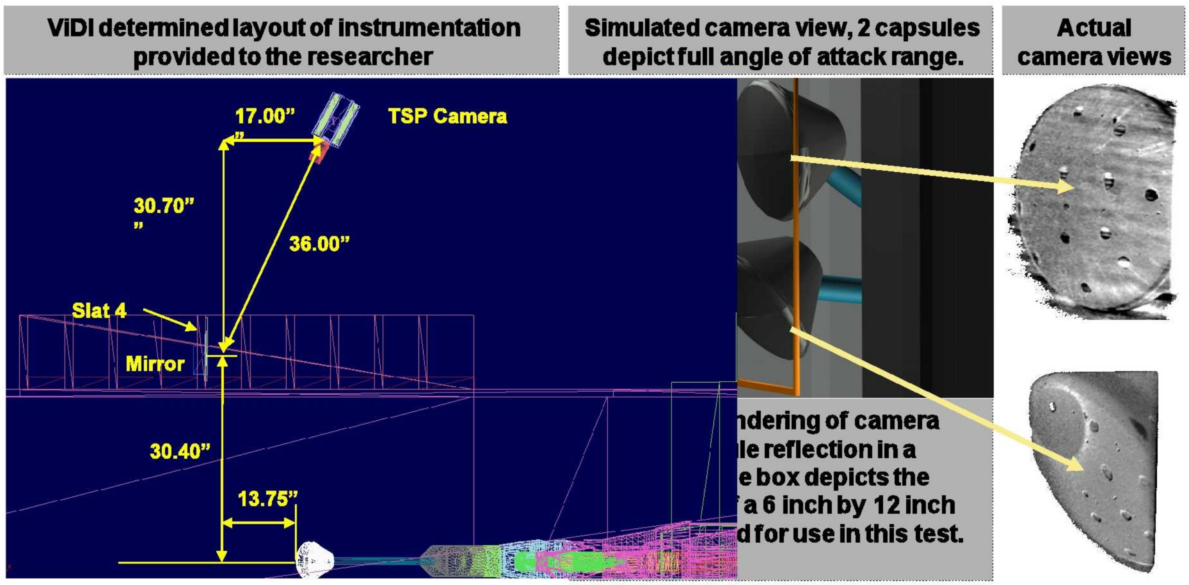

Figure 9. Images depicting the planning and the actual view of a camera used for TSP testing in the NASA LaRC UPWT.

The second area of ViDI is real-time data visualization.[14] The same three-dimensional model used for planning the test, as described above, is now used to display data. The data is fed into the visualization system either through video cameras, to incorporate live streaming video into the virtual environment, or via a facility Data Acquisition System (DAS), which provides facility conditions and instrumentation data, or both, simultaneously. The result is an interactive three-dimensional virtual environment in which hundreds of channels of data of several different formats (video, pressure, temperature, position, rotation, and more) can be displayed *in-situ*. This allows the researcher to see the global distribution of the acquired data in real time, especially if the data sets consist of dozens to hundreds of discreet points, i.e., pressure from static ports or temperature from thermocouples.

In addition to real-time experimental data, the ViDI system has been used to display comparisons between CFD and experimental data in real time. A pre-computed database of CFD data is made accessible to the ViDI system. This is illustrated in Fig. 10, where each black bar represents a surface pressure measured by a static pressure tap. The red bars represent matching CFD data, and the yellow bars are the difference. The surface color on the model is Coefficient of Pressure, as derived from CFD. The ViDI software will retrieve the proper solution for the given test condition automatically based on key parameters reported to it via the DAS. These parameters may include Mach number, angle of attack, Reynolds number, etc. The CFD is shown alongside the experimental data, and real-time differencing is displayed. The real-time cross check between CFD and experiment has proven very valuable in assuring that the experimental conditions are able to meet the CFD, even if those conditions are not what were originally predicted.

The third area ViDI has been applied to is data unification after a test. Here, disparate data sets which may not have been taken at the same time can be put together and displayed in a common format, again using the foundational geometry created in the pre-test planning stage. Figure 11 illustrates post-data visualization of a thermal image depicting the temperature on the base of the model, and the bars emanating from the back of the cylinder representing the pressures on the cylinder in a high-speed boundary-layer flow. Imagery such as Schlieren or laser light sheet flow visualization can be combined with surface data to tell the cause-and-effect story, which will more thoroughly provide knowledge about the global flow field environment.

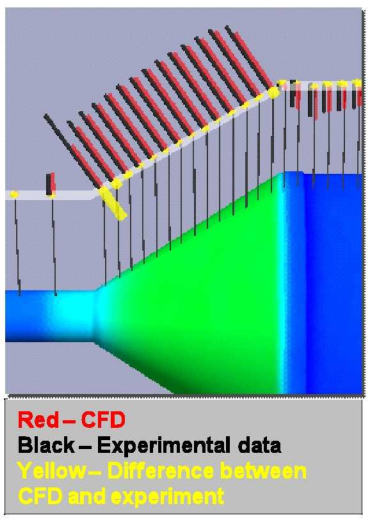

Figure 10. Image created during real-time testing of the Ares 1 rocket.

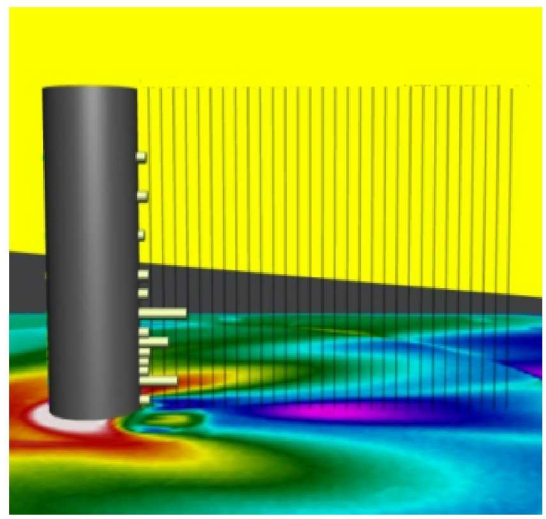

Figure 11. Post-test data visualization of the wake behind a cylinder in a supersonic boundary layer flow. Flow is from left to right.

Figure 12 is showing thermal imagery on the Orion capsule in concert with the Schlieren data, placed in context with the facility.

The ViDI software has become a powerful tool for a wide range of aerospace testing applications. The ability to rapidly combine experimental and computational data sets with three-dimensional geometry into one interactive environment gives the user a greater situational understanding throughout a test. ViDI will continue to grow its visualization capabilities in support of ground test applications.

Figure 12. Post-test data visualization showing IR camera thermal imagery mapped onto the Orion capsule with corresponding Schlieren flow visualization imagery.

VI. Advancing Virtual Presence (for Training)

An additional obstacle to overcome is that of developing a workforce that is thoroughly trained in the operation and installation of these advanced testing techniques. We have found that developing training tools that use animation can be a very effective way to communicate the complexity of advanced testing technologies. Figure 13 shows a frame out of a recently created "Balance" animation, designed to show technicians the fundamentals of how a balance works and where the key sensors are for each component of aerodynamic forces and moments. This example was made in only 80 hours of working time by an animator at LaRC. Note that it shows the test section of the NTF with the side door closed. These animations are easy to generate as CAD/CAM models of nearly all of our facilities and all of the test articles in the facilities are always generated before anything is manufactured. This illustration used existing "wire frame" models of the test section and of the model and balance. Figure 14 shows the animation after the tunnel door is opened, a trivial task to do with such a model.

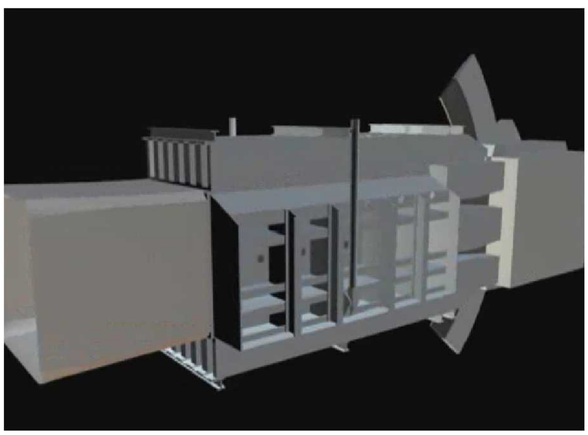

Figure 13. Beginning of a balance animation that shows the NTF Test section.

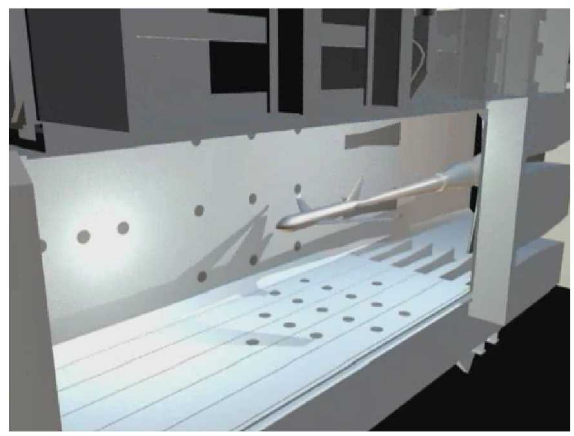

Figure 14. Balance animation showing opening of the NTF Test section.

Figure 15 illustrates another feature of such animations, the ability to show structures as "transparencies," so it is possible to see the balance within the model. It is easy to show important features, and to show the tunnel technician where there are areas of close tolerances between the model and the sting/support structure. While balances are designed to be extremely stiff, they are still manufactured such that some component within the balance flexes. This is where strain gauges are affixed to indicate loading in each of the six principal force and moment directions. It would be desirous to have an infinitely still balance with good resolution of forces and moments, but this is not possible.

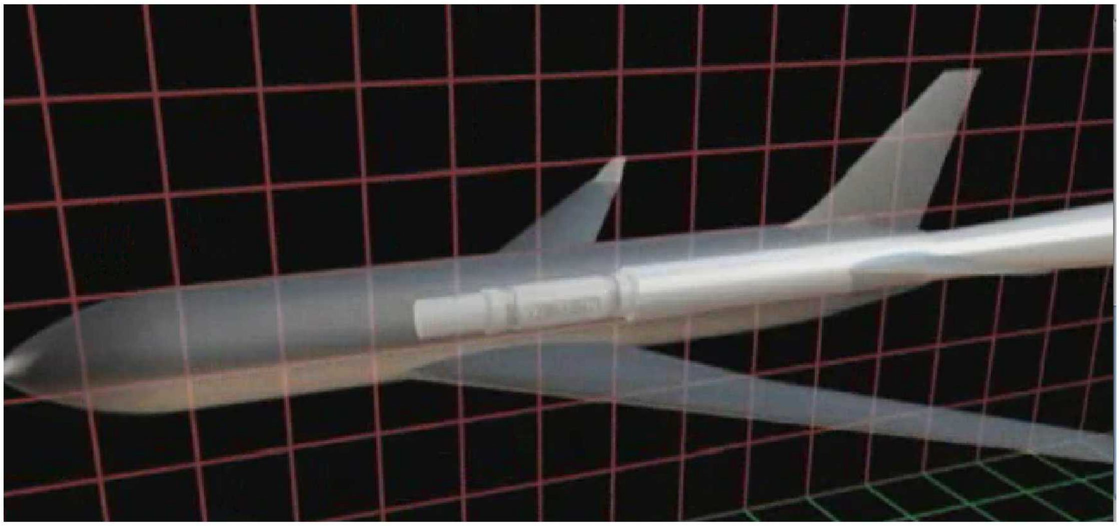

Figure 15. Balance animation showing where the balance is located within the model.

Figure 16 illustrates the effect positive normal force has on the balance, showing very exaggerated deflections of the balance flexures. Figure 17 shows the specific location of the flexures and gauge locations that detect normal force. These types of animations can be done for any instrument, showing the salient features much better than can be done in still images or in front of the actual instrument.

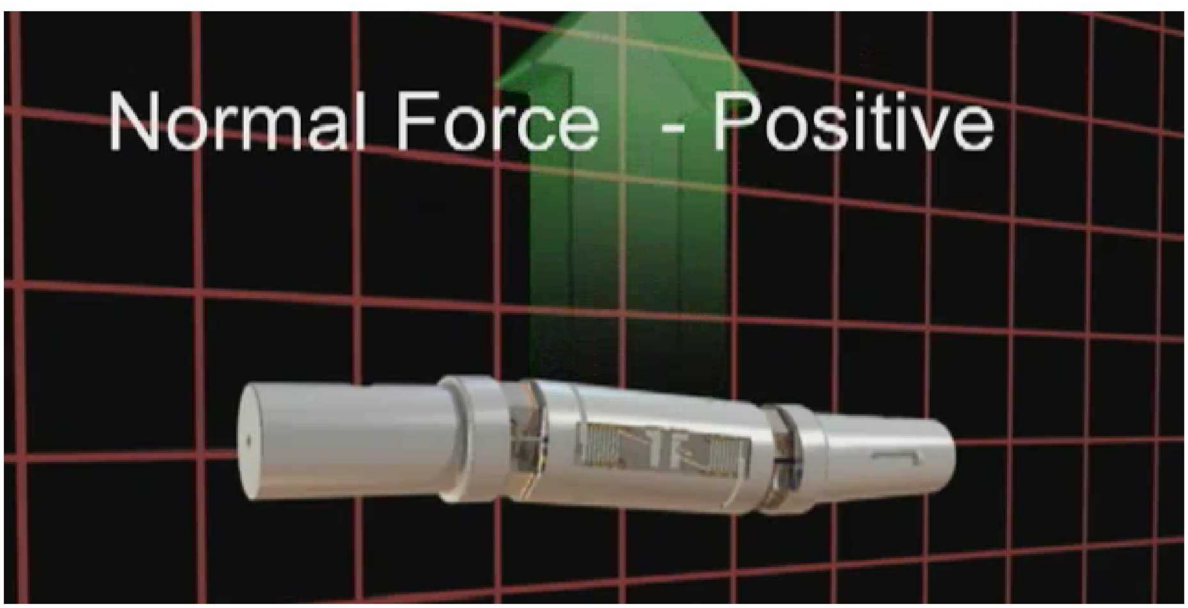

Figure 16. Balance animation that shows how the Positive Normal Force is measured (with exaggerated deflections).

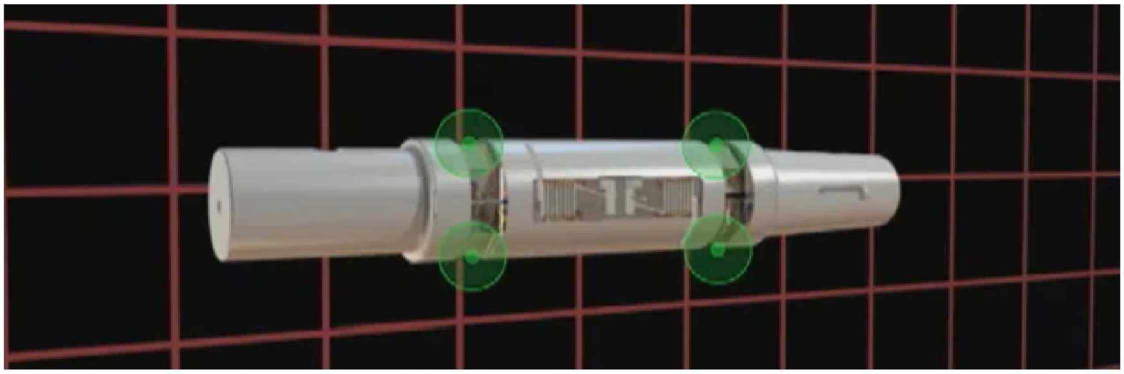

Figure 17. Balance animation that shows the gauges used to measure Normal Force.

It is clear that more integrated high-speed computational capabilities are central to the development and widespread use of any of these techniques. It is also clear that the world's interconnectedness is rapidly advancing, and we expect it to get better in every aspect. Langley has made several investments and pilot efforts, that are currently ongoing, to begin the transformation and accommodate these changes that are inevitably going to happen. We have undertaken several "Technical Challenges" to position ourselves for the 21st century laboratory environment. These are addressed in a companion paper, "Langley Ground Facilities and Testing in the 21st Century."

VII. Concluding Remarks

Several advanced technologies have been discussed which illustrate advancements that are rapidly enhancing the use of the facilities, ensuring they will be viable well into the 21st century. First, very high-speed imaging, which has been aided by the advancement of very high-speed cameras and a novel development in laser illumination of these flows, can bring revolutionary changes to our understanding of hypersonic flow phenomena. Similarly, DP-CARS has been developed to study supersonic combustion, providing valuable benchmark data for comparison with CFD. In order to get more out of each wind tunnel test with every run, it is necessary to continue developing these advanced measurement technologies. Furthermore, to make the most of each run in these facilities, we study the *gas flow*, not just the effect of the gas on the model. PLIF, CARS, LITA, Rayleigh, Diode laser absorption, and other off-body techniques can help obtain important information from each tunnel run, compared to just studying force and moment data. Second, the migration of testing practices toward the use of MDOE will allow additional insights into the phenomena under investigation. The aeronautical testing community should adopt these practices, many of which have been in common use in every other scientific discipline for quite some time. Third, advanced virtual diagnostics tools can merge the worlds of experimentation and computation, allowing a deeper understanding of the phenomena under investigation. Finally, the use of advanced animation through images that represent complex instruments allows the portrayal of the test instrumentation for those who have to work with the instrumentation daily in the facilities.

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