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ABSTRACT

The objective of this paper is to compare the current state-of-the-art of the following three optical techniques under study by NASA for measuring model deformation in wind tunnels: (1) video photogrammetry, (2) projection moiré interferometry, and (3) the commercially available Optotrak™ system. An objective comparison of these three techniques should enable the selection of the best technique for a particular test undertaken at various NASA facilities. As might be expected, no one technique is best for all applications. The techniques are also not necessarily mutually exclusive and in some cases can be complementary to one another.

INTRODUCTION

Model deformation may be defined as the changes in shape of a wind tunnel model (particularly the wings and control surfaces) under aerodynamic load. These changes in the design geometry can cause differences between the acquired and expected wind tunnel results if the expected results are based upon rigid body assumptions. Differences can also occur between acquired wind tunnel data and computational predictions based upon rigid body assumptions. These differences can lengthen and degrade the aircraft design process. The measurement of model deformation has thus been of interest for a number of years. The accurate prediction, as well as the measurement, of model static aeroelastic deformations is becoming increasingly important, especially for transonic transports. It is essential to accurately predict deformations in the wind tunnel in order to duplicate the desired CFD configuration. Deformations must often be taken into account when comparing CFD predictions to experimental measurements at off-design conditions. Increased reliance is being placed on high Reynolds number testing for configuration development and CFD validation, making accurate predictions of static aeroelastic deformations very important, since deformations increase significantly at the higher dynamic pressures associated with high Reynolds number testing. Computational methods such as the finite element method (FEM) need to be calibrated and validated with wind tunnel model deformation measurements in order to ensure accurate predictions[1].

Constraints on optical access, such as limited view ports, illumination, and targeting options often contribute to the requirement for custom, instead of commercial, measurement systems for large wind tunnels. Two custom techniques being developed and applied by NASA to measure model deformation are video model deformation (VMD)[2] and projection moiré interferometry (PMI)[3]. The rapid development of relatively low cost electronic imaging, driven largely by the consumer video market, coupled with improvements in low cost computing have benefited the development of custom VMD and PMI techniques for the measurement of model deformation in NASA wind tunnels. VMD is based upon digital photogrammetry (or videogrammetry) using recorded and processed digitized video images from a CCD camera (figures 1, 2). Single-camera, single-view photogrammetry is then used to determine object plane coordinates and angles corresponding to targets placed at known semispan locations. A near real-time target-tracking version of VMD has been developed under NASA contract by the High Technology Corporation[4]. Projection moiré interferometry (PMI) (figure 2) is a video-based global technique allowing spatially continuous model deformation measurements to be acquired over the entire camera field-of-view, without the use of targets. The topology of the deformed surface can be determined through off-line image processing.

The third technique under study by NASA for both model attitude and model deformation measurements is the commercially available photogrammetric system, made by Northern Digital, Inc. known as the Optotrak™ RH-2020 (figure 3). This system has been successfully used for both aeroelastic and angle of attack measurements, in wind tunnel and flight tests[5]. The Optotrak™ system, which utilizes photogrammetry of synchronized and discriminated infrared emitting

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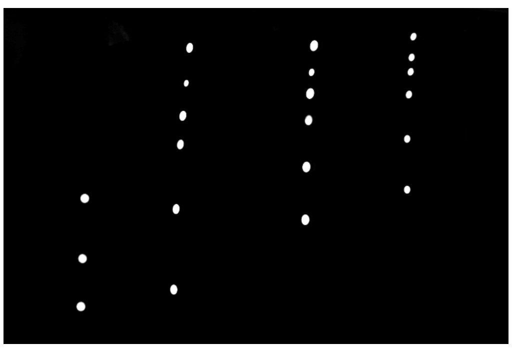
diode (IRED) targets to determine three-dimensional spatial coordinates, is being investigated by several aerospace organizations in addition to NASA for various wind tunnel measurements.

The three optical techniques to be compared here are in various stages of development. Each has advantages and disadvantages, depending on the nature of the test. The VMD technique has been used at five NASA facilities at the Langley and Ames Research Centers for a number of sting mounted and semispan models including low aspect ratio high-speed research and

(a)



(b)

Figure 1. (a) Retroreflective tape targets on semispan model used for Video photogrammetry. (b) High contrast image from CCD camera suitable for automated deformation measurements.

for high lift, transonic, and supersonic testing. The PMI technique has been used at Langley facilities for rotor blade and semispan model testing. PMI measurements of rotor blade position, deformation, and twist obtained at the 14- by 22-Foot Subsonic Tunnel were synchronized with rotor azimuth to determine azimuth dependencies in the flow field and changes to rotor blade orientation. The Optotrak^{TM} system has been used at the Langley 14- by 22-foot Subsonic Tunnel for the primary angle-of-attack measurement for a month-long semi-span model test, but has not yet been used for model deformation measurements at Langley. Plans to

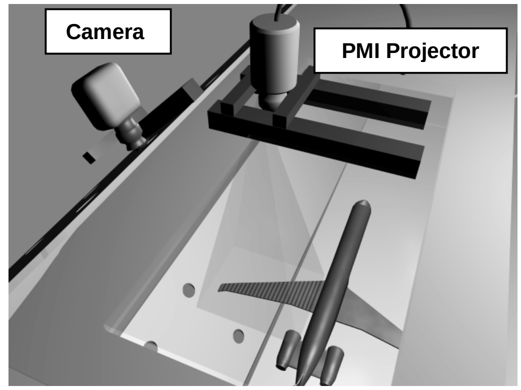


Figure 2. Typical VMD (camera only) or PMI (camera and projector) implementation as a wind tunnel model deformation instrument.

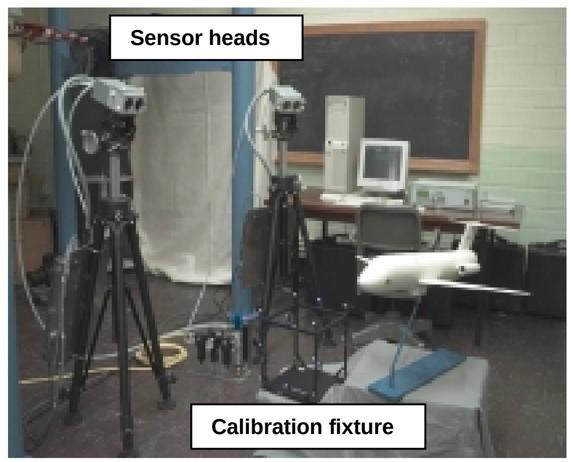


Figure 3. Optotrak^{TM} setup in laboratory showing sensor heads and calibration fixture.

employ Optotrak^{TM} for static and dynamic deformation tests at the Langley Transonic Dynamics Tunnel are in progress. Similar RH-2020 systems have been used at Boeing and NASA Ames Research Center for tunnel tests.

After brief discussions of the three techniques are given, the relative merits and operating characteristics of the three techniques will be discussed and compared. The important issues of spatial and temporal resolution and accuracy will be compared. A comparison of the model surface preparation requirements (including possible deleterious effects on aerodynamic data) and time required for any preparations for each of the three techniques will be made. Environmental issues (including safety, temperature, and pressure) will be compared. The accommodation of different model configurations by the three techniques will be addressed. The ease of operation, time required for data reduction, and data output formats will be compared. The global measurement capability of each technique will be contrasted. The potential of each technique for future enhancements will be discussed, and the limitations of the techniques will be pointed out. Efforts to remove or reduce these limitations will be discussed. The potential for operation of the three techniques simultaneously with other advanced optical techniques such as temperature and pressure sensitive paints (TSP and PSP) and Doppler global velocimetry (DGV) will be discussed and compared. The potential of these methods for other applications, such as dynamic measurements, deflection analyses of test section walls, or in-flight deformation measurements, will also be discussed.

DESCRIPTION OF METHODS

Video Photogrammetry

Video photogrammetry (VMD) development with multiple cameras was initiated in the 1980s [6], based on earlier successful wind tunnel tests conducted in the 1970s using film cameras[7]. The introduction of image processing routines coupled with the development of a simplified single-camera, single-view technique permitted automated data acquisition and reduction. These developments facilitated near routine use in production wind tunnels[8]. The development of a target-tracking version of VMD under NASA contract is discussed in reference 4. A review of VMD can be found in reference 2.

The VMD technique consists of a single-camera, single-view, photogrammetric solution from digital images of targets placed on the wing at known semispan locations (figure 1). Since only one camera is required, lighting problems are lessened considerably, which is especially advantageous when using existing test section illumination. Except for these targets, which may have some minor effects on the aerodynamic data, the technique is non-intrusive. The basic hardware consists of a standard video-rate CCD video camera, a light source usually located as close to the camera as possible (when retroreflective targets are used), a frame grabber board, and a computer with image acquisition and reduction software. The camera is positioned to the side and somewhat above or below the model, resulting in an oblique view of the model. A target row is typically placed on or near the fuselage to serve as control in addition to target rows at known semispan locations along the wing. Image processing is used to automatically locate and compute corrected image plane coordinates for each of the targets. Single-view photogrammetry is then used to determine the *X*

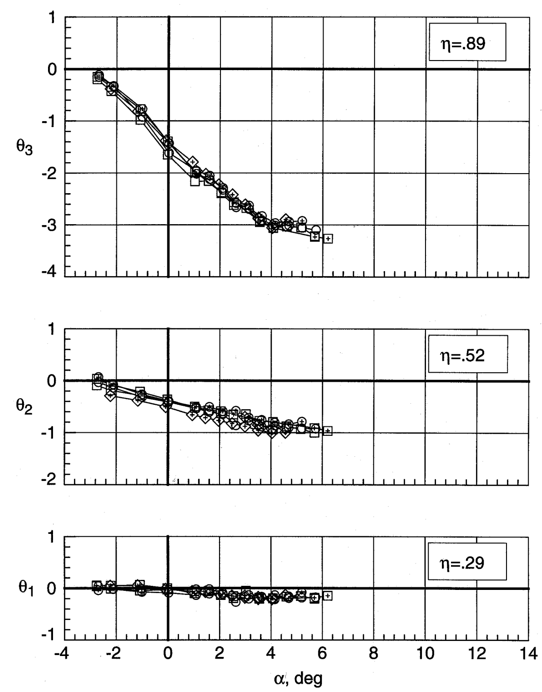


Figure 4. Change in wing twist (θ) versus angle-of-attack (α) at constant Q and varying Reynolds number at 3 semispan stations (η).

(streamwise), *Z* (vertical) coordinates in object space, given the known *Y* (crossflow) coordinates. Vertical displacements at specified chordwise locations and slope angles are computed by linear least squares for each semispan station along the wing.

The image processing routines used in VMD make the technique amenable to online data reduction. These routines consist of blob analysis for target location, simple threshold removal, and computation of image centroids to determine the target positions in pixels on the image plane. Reduced deformation data can be available within a few minutes of the completion of a set of runs (including wind-off calibration runs) in some cases. In some system versions, the angle and Z-displacement are computed as each data point is taken. Twist and bending are computed after angle correction and referencing to the wind-off polar(s) at the conclusion of a set of runs. The reduced data is then transferred to the tunnel data acquisition system (DAS) for merging with standard tunnel data. The target-tracking VMD system developed by High Technology Corporation produces centroids at a 15 Hz rate when triggered. The system has a quick look capability with final data reduction accomplished at the conclusion of a series of runs.

Dedicated VMD measurement systems are now operational in 5 tunnels at Ames and Langley. These facilities are the National Transonic Facility (NTF), the Transonic Dynamics Tunnel (TDT), the Unitary Plan Wind Tunnel (UPWT), and the 16-Foot Transonic Tunnel (16-TT) at NASA Langley and the 12-Ft Pressure Tunnel at NASA Ames. While each of these facilities presents unique challenges to the installation of measurement systems, the most difficult instrumentation challenges occur at the NTF. Constraints imposed by operation in a high-pressure environment over a wide temperature range (+60º C down to -160º C) have had a significant impact on the continuing development, improvement, and optimization of instrumentation at the NTF (particularly for the measurement of model deformation). Examples of the change in wing twist (θ) versus angle-of-attack (α) at constant Q and varying Reynolds number at 3 semispan station (η) are presented in figure 4 for a generic transport at the NTF. Data are presented from 3 runs that were taken over a period of 2 weeks and over a total temperature range of over 100° C. The data indicates nearly constant wing shape with varying Reynolds number.

Projection Moiré Interferometry

PMI is an optically simple, non-contacting measurement technique used since the 1970's for surface topology and shape characterization[9]. The fundamentals of PMI are well known[10, 11], but only recently have PMI and similar systems been used to quantitatively measure wind tunnel model deformations while under aerodynamic load. PMI development for wind tunnel model deformation measurements is described in references 2, 3, and 12.

Conventional PMI relies on the projection of a grid of equally spaced, parallel lines onto the wind tunnel model surface. Any incoherent light source providing adequate illumination levels can be used for grid line projection. A pulsed laser diode bar emitting in the near infrared is often used for wind tunnel testing because it allows lights-on tunnel operation without sacrificing grid line contrast and provides the high illumination levels required to measure large fields-of-view. Although laser illumination has the potential to cause speckle noise in the acquired PMI data images, diodes with 3 nm or greater emission linewidths are used to greatly reduce this problem. A Ronchi ruling (a transmissive grating with opaque parallel lines etched at equal spacing and thickness) installed in the projector system is the physical element generating the projected grid lines. The projector system is typically aligned such that its optical axis is perpendicular to the surface being measured. Surface preparation is generally not required for non-metallic models, but polished metal models may require painting to obtain a diffuse scattering surface.

A CCD camera with a narrow bandpass filter matched to the projector illumination wavelength is positioned to view the model at a 30-45 degree angle inclined from the projector optical axis. Images of the grid lines projected onto the model are acquired in non-deformed (wind-off) and loaded (wind-on) conditions using a frame grabber installed in a PC-compatible computer. Image processing routines are then used to remove camera perspective distortion and "interfere" the acquired images with a computationally generated reference grid, resulting in interferograms containing moiré fringes. These fringe patterns (figure 5) are

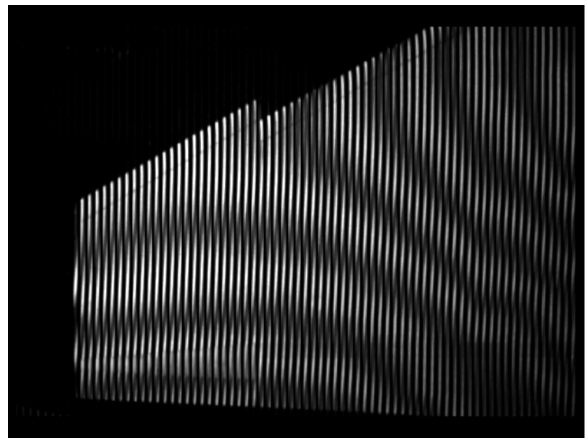


Figure 5. PMI Moiré fringes generated by interfering PMI projected grid lines.

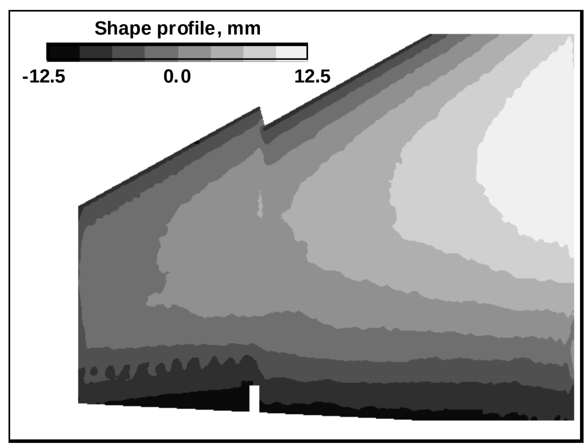


Figure 6. PMI-measured airfoil shape data obtained by processing moiré fringe images as in figure 5.

further processed offline to obtain a quantitative, spatially continuous representation (figure 6) of the model surface shape or deformation[3]. The current PMI image processing code can process a single image in approximately 20 seconds on a 400 MHz Pentium II PC. On-line data processing is not feasible at these rates, but key datasets can be processed overnight. Efforts are currently under way to reduce the data processing time, and it is believed that a factor of 4 reduction can be achieved by time optimizing the processing code and using image processing routines designed to exploit the multimedia acceleration capabilities available on Pentium-class processors.

PMI has been used in the LaRC 14- by 22-Foot ST, TDT, and UPWT since the beginning of the LaRC PMI development effort in 1996. Facility dedicated PMI systems are currently under construction for the LaRC 14- by 22-Foot ST and TDT. Both systems will be capable of acquiring deformation measurements of fixed wing models, and will have conditional sampling capabilities for measurement of azimuth dependent rotorcraft blade deformation. PMI may prove particularly useful in the TDT since the facility is primarily used for aeroelasticity research. PMI data acquired during the onset of aeroelastic instabilities and flutter could be used to fully describe the instability mechanisms via the global model deformation.

Photogrammetry Using Optotrak™

The Optotrak™ system referred to here is the RH-2020 produced by Northern Digital Incorporated (NDI) of Ontario, Canada. The basics of the component structure of this system and its features and operation are described in NDI manuals[13, 14, 15]. The RH-2020, designed for use in aerospace research, was first delivered to the Boeing Company in 1989. Recently several major aerospace research facilities have procured the RH-2020 to enhance capabilities to measure displacements and angles of wind tunnel models *in situ*.

The RH-2020 consists of six basic parts: (1) cameras (heads and bodies); (2) cooling system; (3) system control unit; (4) computer; (5) markers with strober; and (6) calibration frame. The camera sensors are two orthogonally-mounted linear CCD arrays, 2048 pixels each, which are infrared sensitive. Each array is optically coupled with an appropriately oriented cylindrical lens, all mounted in a sealed box. Closely coupled by electrical cable and pneumatic air line to each camera head is a camera body. The camera body is electrically powered and houses the necessary computer components to control and support the camera head. The camera head and body function as a unit for image gathering and processing. For an RH-2020 system, two of these cameras are controlled by a system control unit (SCU) in conjunction with a personal computer (PC). The SCU is a powered unit with data acquisition and control cards and software that supports communication to and from the PC and cameras. Basic operating software supplied by NDI converts camera image pixel coordinates to object field data with close-range photogrammetric algorithms.

Small infrared emitting diodes (IREDs) are employed as targets which are mounted rigidly in or on the object to be measured. These are strobed at defined rates in a specified order with the particular emitting marker identified. The SCU controls this process through the strober device at rates up to 3500 Hz, which is the combined rate for all markers present (usually 6 or more). The highest effective data rate for an individual marker appears to be about 260 points per second from tests conducted to date. (NDI suggests that 12 markers, defined in two groups of 6 each, can be characterized and measured at up to a 45 Hz rate.)

Langley has two of the RH-2020 systems. The first has been used in the 14- by 22-Foot Tunnel for 5 tests, primarily measuring angle-of-attack or pitch angle for semi-span models. Laboratory testing has included dynamic measurements on a sting-whip apparatus, some preliminary measurements of time behavior for a flat aluminum plate, and measurements of angles (pitch and roll) on calibrated turntables (accurate to 1 arcsecond).

UNCERTAINTY

Optotrak™ is the most accurate of the three systems, with a laboratory precision approaching 0.001° and an accuracy, compared to a standard, of 0.01° over a 40° range. The precision and laboratory angular accuracies of VMD are about twice as large as that of Optotrak™. PMI, while quantitatively the least accurate of the three, may in some special cases actually yield superior data by using its global measurement capability to determine deformation that may possibly be misinterpreted with the limited spatial sampling of VMD or Optotrak™.

The VMD system resolution depends on the fraction of the image field that the targets occupy. For cases in which the row of targets span nearly the entire image plane, sub 0.01° resolution is possible in the laboratory. Wind tunnel AoA tests using body targets indicate that 0.01° resolution can be achieved during wind-off tests and may be possible for wind-on tests, provided that the target row(s) occupy nearly the entire image plane and, in addition, model translations while changing pitch are not excessive. However, the fraction of the image plane occupied by a target row near the wing tip may be less than 25% in order to simultaneously image the inboard portions of the wing and body. Thus a typical angular resolution for model deformation measurements may be 0.05° or larger near the wing tip due to the small fraction of the image plane occupied by the row of targets at the tip. Displacement measurements in the laboratory have an uncertainty approaching 0.025 mm with a precision of 0.003 mm, but displacement measurement uncertainty in large wind tunnel facilities is generally 5 to 10 times worse than laboratory values.

PMI system resolution is primarily dependent on the video camera field-of-view, optical modulation transfer function, and illumination/observation angles. Deformation measurement resolutions better than 0.05-mm have been attained with conventional laboratory systems using 640-x 480-pixel video cameras with a 300-x 300-mm field-of-view. Absolute deformation measurement accuracies for similar laboratory systems have been shown to be better than 0.15-mm over a 50-mm range of deformations[16], equating to angular uncertainties better than 0.05°. Scaling these accuracy and resolution values to a 1.2-x 1.2-meter field-of-view representative of a large wind tunnel application, an absolute accuracy of approximately 0.75-mm with a deformation measurement resolution of 0.25-mm is estimated using the current technology. PMI system hardware and software enhancements currently being implemented will help to progress the system to the instrument measurement goals of 0.25-mm absolute accuracy and 0.1-mm resolution.

The Optotrak™ spatial resolution quoted in the NDI descriptive literature is based upon 1/100 pixel, yielding 1 part in 200,000. This image plane spatial resolution must be converted into object plane magnitudes based upon a particular choice of lens and experimental setup. Position and angular accuracies are cited by NDI as .15 mm and $.01^{o}$ for one particular instance, and repeatability as approximately 1 pixel width (.01 mm). At NASA Langley, angles have been measured with uncertainty as small as $\pm 0.01^{o}$ over a range of -10^{o} to 30^{o} in the wind tunnel environment and $\pm .002^{o}$ over a range of -20^{o} to 20^{o} in the laboratory environment. These values are appropriate for a 1-meter cube in the center of the camera field of view. The object distances in the laboratory case were 2 meters and in the wind tunnel case were 6 meters.

MODEL SURFACE PREPARATION

A target row consisting of 2 or more targets is typically placed on or near the fuselage to serve as control in addition to target rows at known semispan locations along the wing for VMD. Flat black paint has been used in the past to remove glints and increase target contrast at facilities where surface finish requirements will allow. Retroreflective tape targets provide a high contrast image for VMD when illuminated by a light source placed close to the camera. High contrast images are more amenable to automated target location by digital image processing and make VMD more immune to test section lighting used for surveillance. However, retroreflective tape has a step height of 0.1 mm with a surface roughness of 5 µm, which is not acceptable at a facility such as the NTF where surface finish requirements are very stringent. In addition, at the NTF it is difficult to locate a light source sufficiently close to the VMD camera. Thus a special polished paint technique for targets has been developed for the NTF and investigations continue on improved targeting schemes that may also be advantageous at other facilities. Experiments are ongoing to improve existing methods and develop new methods for applying targets for model deformation that lessen their potentially negative effect on aerodynamic data. Milled targets have been tested with filler over white paint, retroreflective tape, fluorescent dye and filler mixture, and retroreflective paint. Advantages of milled targets, besides removing the step height, are that the targets are permanent and target coordinates can be accurately determined with a 3-D coordinate measurement machine prior to testing. Subsequent tests with the model can make use of these permanent targets without reinstallation or remeasurement, eliminating that setup time. If retroreflective tape is placed in milled locations, the step height is removed, but the surface roughness remains an issue. Retroreflective tapes with surface roughness down to 0.5 µm are available, but the light return from these tapes is reduced. For polished paint targets applied directly to the wing surface there is no abrupt step (only a gradual rise to 0.01 mm with surface roughness of 0.3µm) compared to the tape targets without milling. However, specialized skill is needed and the target application time (including paint drying time) can be as long as a shift for the polished paint technique without milling. For paint in milled targets, time must still be allowed for drying, but the skill required to apply the targets is reduced substantially. Given the advantages of milled targets, it has been recommended that retroreflective tape (or polished paint) milled targets be considered during model design when deformation measurements are anticipated with the VMD technique.

PMI requires minimal or no surface preparation in a majority of cases. The only surface requirement is that the surface diffusely scatters enough of the PMI projection system light to be observed by the PMI video camera. This characteristic will be common among plastic, fiberglass, wooden, composite, painted, and many metallic models. Highly polished metallic models having a mirror-like finish, such as those used in the NTF, will generally not return enough scattered light to the video camera to be measured. However, if PSP or TSP measurements are to be acquired on these models, the PMI system can measure deformations in those regions where the PSP/TSP has been applied, as the paint generates a diffuse scattering surface.

Optotrak™ requires that IRED markers be placed within the surface to be measured. This placement combines technical considerations with art. Appropriate small holes are drilled as needed and the IREDs glued in place within these. Generally, the marker must be covered with a transmitting material (often clear UV curable resin) and the cured surface smoothed. That usually entails sanding with successively finer grades of sandpaper. The time required to place markers into a model, considering the mounting, covering, curing, and polishing, may require as much as a day or so to complete. Determining the pattern for the markers and preparing the surface increases the time required, which may vary widely depending upon the particular test. Thin wings or other thin surfaces pose installation problems. The two very small connecting wires for each IRED must be run through the model to mate with the strober. Locating the markers to keep at least three (and usually more for redundancy) in view all times provides a constraint.

ENVIRONMENTAL REQUIREMENTS

The CCD camera used in typical VMD and PMI measurement systems must be protected from extremes in the operating environment. Typical temperature and humidity operating requirements are 0 to 40° C with a relative humidity of 50 to 70%. Environmentally protected pressure housings that can supply heat or cooling are used at the NTF for the VMD cameras due to the large temperature and pressure excursions at that facility. A vortex cooler is used at the 16-Ft Transonic Tunnel to direct cooled air onto the VMD camera located in the plenum. Tests at the NTF have shown that it is generally advantageous to hard-mount a camera rather than mounting it on a pan-tilt unit that may be subject to movement under flow conditions.

The laser diode based PMI projection systems being used for current and future wind tunnel tests at LaRC are relatively immune to wind tunnel environmental extremes. The laser source and all associated projection system electronics are housed in a single unit located in the tunnel control room, isolated from the environmental extremes. The laser light is then fiber optically coupled to a small projector head located in or about the tunnel test section. The projector head consists only of a Ronchi ruling and projector lens. The fiber cable is an 800 micron, single core multimode fiber, armour coated to withstand the harsh tunnel environment. Typical fiber lengths are 25 to 35 meters. The methodology of fiber optically coupling the laser light to the projector head will work in most facilities, but the ability of the fiber to survive the cryogenic temperature extremes of the NTF has not yet been assessed.

PMI systems employing laser diodes as the illumination source have an associated safety concern. Most laser diode bars suitable for wind tunnel applications are class IV laser sources, requiring appropriate eye protection and safety interlock procedures to be in place. However, light exiting the PMI system projection head is highly divergent, which greatly reduces the risk of ocular injury from specular or diffuse reflections that may contact personnel outside the immediate measurement area.

The electronics within the environmentally sealed units of an Optotrak™ sensor head create sufficient heat that constant flow cooling must be maintained in order to avoid data loss or equipment loss. The cooling system consists of a standard vortex tube and manifold assembly, designed to operate up to four lines that supply cooled air to camera heads and bodies and to other peripheral devices. In-line air filters keep the recipient system components clean. Shop air at 100 psi is usually supplied, and the cooling will typically require 25 – 40 psi. However, the tubing length will dictate these conditions, and loss of cooling presents significant difficulty. The sealed units permit operation at pressures from ¼ to 4 atmospheres and temperatures of -10^{o} C to 60^{o} C in addition to reducing the effects from dust and moisture.

Fog in the test section, which is possible in some transonic facilities, will affect the imaging of VMD and PMI similarly. However, since fog will also degrade the projected grid, PMI data may be affected a little more by fog than VMD. The active IR targets of Optotrak™ would be expected to make that measurement system the least sensitive to fog in the test section since only a single transmission of the light (from the IRED to the sensor heads) is affected.

MODEL CONFIGURATION CONSIDERATIONS

A number of deformation measurements have been made with the VMD technique on various models at 5 NASA facilities. These measurements were made on full span models that were sting mounted and post mounted in addition to sidewall and floor mounted semispan models. However, single-camera implementations of VMD are valid for pitch sweeps only. PMI measurements have been acquired on sting mounted rotorcraft and full span fixed wing models, in addition to wall mounted semispan models. Few problems are anticipated for PMI measurements in other configurations. Optotrak™ has primarily been used at Langley with vertical semispan models for angle-of-attack measurements.

OPERATIONS

Experimental setup

All three techniques can be set up in the laboratory in a few hours. One of the major differences between the techniques regarding wind tunnel installation is that VMD requires only one viewport whereas PMI and Optotrak™ each requires two separated viewing angles and hence two viewports. PMI and VMD require similar cabling for their video cameras, but PMI has additional cabling requirements for the laser diode illuminator. The Optotrak™ sensor heads and cabling are considerably larger than the typical video cameras and cabling used for PMI and VMD.

Lighting

The basic restrictions for the techniques are that a suitable view of the area of interest must be available with sufficient light from the area (or targets) reaching the sensor(s). PMI employs infrared illumination and filtering that makes it relatively insensitive to the test section visible lighting used for model surveillance. Optotrak™ uses IREDs and filtering that also make that approach relatively independent of test section lighting. VMD systems work best with retroreflective tape targets. For a VMD system that utilizes retroreflective targets, it is desirable to illuminate the model with a light source mounted near the camera. Since the CCD camera is sensitive to a wide variety of wavelengths, the spectral characteristics of the lamp are not significant. Since retroreflective tape targets are not acceptable for most tests at the NTF, a special technique was developed that makes use of white paint polished targets. The stringent surface finish requirement of cryogenic models results in mirror-like surface finishes. High contrast targets are produced at the NTF by ensuring that the reflections seen in the highly polished model are black by painting the opposite test section wall and part of the ceiling black. Thus a high-contrast image is developed that is much more amenable to automated image processing routines. However, since test section lighting is used for illumination, conflicts with surveillance requirements may arise.

Calibration

The initial pre-test calibration procedure for the VMD technique determines those camera parameters necessary for conversion from pixels to corrected image plane coordinates. A similar procedure is used for Optotrak™ at the factory to determine calibration coefficients that are not generally modified unless Optotrak™ is returned to the factory. The distortion model is given by the following set of equations:

$$\begin{aligned} \delta x &= x\, r^2 K_1 + x\, r^4 K_2 + x\, r^6 K_3 + (r^2 + 2x^2) P_1 + 2xy P_2 \\ \delta y &= y\, r^2 K_1 + y\, r^4 K_2 + y\, r^6 K_3 + (r^2 + 2y^2) P_2 + 2xy P_1 \end{aligned} \quad (1)$$

where the point of symmetry for distortion has already been subtracted from x and y. If the image plane is perpendicular to the optical axis, the point of symmetry and the photogrammetric principal point coincide. Typically the 3rd order radial distortion K_1 is the dominant term. In addition, the asymmetrical terms P_1 and P_2 are small and projectively coupled to the point of symmetry and external orientation of the camera.

In the VMD technique, the photogrammetric principal point is found using a laboratory laser illumination technique. The point of symmetry for distortion is determined in situ from the point of image symmetry of the zoom lens[8]. In cases where the video camera cannot be calibrated in the lab the principal point is taken to coincide with the point of symmetry for distortion. The need for extensive camera calibration is lessened somewhat by on-line calibration using the model pitch angle for wind-off reference at the tunnel total temperature and pressure test conditions. The pointing angles and location of the camera in the tunnel coordinate system are determined at the start of the test by photogrammetric resection on a target plate which is aligned to the horizontal *X, Y* plane of the tunnel. The target plate consists of a flat black plate with an array of white or retroreflective tape targets with known locations. The *X*-axis of the calibration plate is aligned parallel to the *X*-axis of the test section coordinate system. The target plate is translated a known amount along an optical rail to several *Y* locations where resections are made. Provided the alignment is correct, the three pointing angles and *X* and *Z* of the camera will be nearly equal at each location of the plate whereas the *Y* value for the camera will follow the change in location. A technique is then used to determine the photogrammetric principal distance that causes best agreement with the changing *Y* values of the target plate if necessary. The technique for determining the principal distance is described in reference 17.

Once the three Euler angles and position of the camera are established relative to the tunnel coordinate system, measurements can then be made on the target plate for an in situ check of the technique by comparing measured and known *Z* values. Providing the *Z* value determinations are reasonable, a pitch polar can then be taken with wind-off to ensure that the change in pitch angles on the wing, measured by the automated system, track with the onboard accelerometer. The final calibration step requires a wind-off pitch sweep at run temperature and pressure over the range of angles expected during the subsequent wind-on testing. A wind-off polar in the middle and at the conclusion of a set of runs is helpful to verify system stability, especially at the NTF during cryogenic operation.

PMI systems are calibrated using a flat calibration plate installed in the facility prior to model installation. For a typical sting mounted model configuration, the calibration plate is installed parallel to the test section floor at the mean vertical height of the model surface to be measured. Both sides of the plate are painted flat white, but one side has a square array of black dots (typically 30-x 30 dots) painted at a known, constant spacing. The card is oriented such that the dots can be viewed by the PMI video camera, and is illuminated by the PMI projector system with the Ronchi ruling removed. Several images of the dot target are acquired and averaged. The average dot card image is then used to determine image warping coefficients used to remove perspective and optical distortions associated with the PMI video camera and lens. After the dot card images have been obtained, the card is flipped so the remaining flat white side of the target can be viewed by the video camera. The Ronchi ruling is reinstalled in the projection system, and grid lines are projected onto the flat white surface. The target is then pitched to known angles, measured by a precision accelerometer, and images of the grid lines projected onto the target are acquired at each known pitch angle. The image sets acquired at each pitch angle are averaged, and the average images are used to determine the moiré fringe contour interval. The fringe contour interval, typically expressed in mm/fringe, is subsequently used by the image processing software to convert the computed fringe patterns to dimensional model shape or deformation data. A wind-off pitch sweep of the model at tunnel operating conditions can be performed to further refine the calibration.

During calibration of the RH-2020 system for a test, the orientation of the cameras is established by first inserting a known array of the markers (or calibration frame) into the field of view. The frame, shown in the foreground beneath the model in figure 3, is an open cube constructed of ½ inch square tubular aluminum with 16 markers angled in one direction with respect to the base. The calibration frame has its own defined coordinate system. When positioned in the field of view of the cameras, in the volume of interest and oriented reasonably close to a desired frame of reference, a satisfactory calibration of the cameras requires just a few seconds of data. At that point the system camera orientation is based upon axes defined by the calibration frame. To reach a final chosen frame of reference for the cameras in the wind tunnel test section coordinate system, additional marker data must be acquired and applied to determine a transformation of the axes for the cameras. Setting the cameras to measure displacements and angles in a user-specified frame of reference with meaningful measurands is normally desired for testing. Real-time data records that provide data in the directly usable format are possible. For example, the time history of displacement of one or more of the markers may be used to extract frequency information.

Issues remain unresolved concerning the calibration and transformation process to achieve the measurements in a desired particular set of axes. Care is required in choosing the orientation of the calibration frame (first step) to facilitate the transformation of the desired final set of axes.. The location of the desired frame of reference is sometimes not initially well defined and the geometry and steps in achieving it may be complicated. Adequate planning and mock-up tests in a laboratory setting before facility entry are highly beneficial.

Data acquisition

All three techniques are able to acquire data at rates that match typical data rates in NASA wind tunnels. The automated target-location-and-identification version of VMD acquires data at a 60 Hz rate, but computes centroids on fewer images (usually 10-15 images) in order to keep up with standard facility data acquisition rates. The VMD target-tracking prototype system developed by the High Technology Corporation records real-time centroids of targets at a 15 Hz rate for later data reduction. PMI acquires images, for later data reduction, without impact on the facility data rate. Optotrak™ typically records and outputs partially reduced data at 50 Hz, but can acquire and process data at up to 250 Hz for a limited number of IRED targets.

Data reduction

The VMD and Optotrak™ approaches are better suited to large data volumes than PMI at current levels of development since PMI image data is processed after acquisition in a non-automated fashion. Both VMD and Optotrak™ make use of the collinearity equations (2) below that are fundamental in photogrammetry. Here x and y are the corrected image plane coordinates (including correction for the photogrammetric principal point x_p, y_p), c is the principal distance (or camera constant) which will be slightly larger than the focal length for finite focal distances, X, Y, and Z are the object space coordinates of the target, X_c, Y_c, and Z_c are

$$x = -c\frac{m_{11}(X - X_c) + m_{12}(Y - Y_c) + m_{13}(Z - Z_c)}{m_{31}(X - X_c) + m_{32}(Y - Y_c) + m_{33}(Z - Z_c)}$$
$$y = -c\frac{m_{21}(X - X_c) + m_{22}(Y - Y_c) + m_{23}(Z - Z_c)}{m_{31}(X - X_c) + m_{32}(Y - Y_c) + m_{33}(Z - Z_c)} \quad (2)$$

the coordinates of the perspective center of the lens, and the *m* terms are elements of the following rotation matrix

$$\begin{aligned}
m_{11} &= \cos\phi\cos\kappa \\
m_{12} &= \sin\omega\sin\phi\cos\kappa + \cos\omega\sin\kappa \\
m_{13} &= -\cos\omega\sin\phi\cos\kappa + \sin\omega\sin\kappa \\
m_{21} &= \cos\phi\sin\kappa \\
m_{22} &= -\sin\omega\sin\phi\sin\kappa + \cos\omega\cos\kappa \\
m_{23} &= \cos\omega\sin\phi\sin\kappa + \sin\omega\cos\kappa \\
m_{31} &= \sin\phi \\
m_{32} &= -\sin\omega\cos\phi \\
m_{33} &= \cos\omega\cos\phi
\end{aligned} \quad (3)$$

The pointing angles of the camera, ω, ϕ, and κ, which rotate about the *X*, *Y*, and *Z* axes respectively, are defined as positive if they are counterclockwise when viewed from the positive end of their axes. For the single-view reduction used by VMD the *X* and *Z* coordinates are determined from the collinearity equations (1) when *Y* is known. Optotrak™, on the other hand, uses 2 views that result in 4 equations in 3 unknowns that can be solved for *X, Y, Z* by least squares (linear least squares can be used if the equations are rewritten as linear functions of *X, Y,* and *Z*).

PMI data images are processed using an image-based phase quadrature technique to determine the global model deformation. Model deformation instigates a change in the spatial locations of the PMI projected grid lines on the model surface compared to a baseline condition. This change in grid line position can be considered a phase modulation of the original projected line pattern. The objective of the processing software is to determine the phase modulation, as it is directly related to the deformation. First, perspective and optical distortions are removed from the raw PMI data image using the warping coefficients determined from the PMI system calibration. The dewarped image is then interfered with a computationally generated reference grid, resulting in an *interferogram*. The reference grid is an image whose intensity varies sinusoidally across the rows at a spatial frequency equal to the projected grid line frequency observed by the PMI system video camera. The interference process is performed four times, with an incremental 90° phase shift applied to the reference grid each time. The interference process generates interferograms with low spatial frequency moiré fringes modulated by high frequency artifacts of the projected grid lines. The high frequency artifacts are filtered from the four interferograms using Fourier transform filtering techniques. After filtering, the deformation-induced phase modulation can be determined by:

$$\theta = tan^{-1}\left[\frac{I_{270} - I_{90}}{I_0 - I_{180}}\right] \quad (4)$$

In equation (4) above, θ is the projected grid line phase, and I_x are four phase shifted interferograms where the subscripts represent the phase of the computer generated reference grid. Equation (4) determines the grid line phase distribution modulo 2π, which must be unwrapped to remove the 2π discontinuities. The quantitative deformation profile is then determined by dividing the unwrapped phase distribution by the effective system wavenumber *k*, where:

$$k = \frac{2\pi}{Fringe\ Contour\ Interval} \quad (5)$$

The fringe contour interval in equation (5) is the amount of deformation each fringe represents in the desired units, determined by in-situ calibrations of the PMI system in the wind tunnel.

Data output formats

VMD reduced data typically consists of change in twist induced by static aeroelastic deformation at the semispan stations where target rows are located for each data point, whereas PMI reduced data typically consists of an image that maps the deformation to gray scale. Scalar values for model bending, twist, or other deformation quantities along any path within the PMI system field-of-view can be determined by further interrogation of the PMI deformation image. Such a data display, while not conducive to large data sets, can be very useful to detect local areas of difficulty within the global image. Optotrak™ data are initially *X,Y,Z* values that are often transformed to angular data.

Data turnaround time

Both VMD and Optotrak™ can approach near real-time analysis of data and so are much more conducive to high data volumes than PMI. VMD data is typically transferred to the facility DAS at the end of a run series. The transfer of reduced data to the facility DAS after each data point has been taken has been achieved with Optotrak™, but not yet with VMD. PMI reduced data (a set of images with gray scale as deformation) is typically not available until a day or so after the data is acquired, especially if large data sets are taken. PMI, in its current state of development, is more properly used for selected evaluations to verify or determine the global behavior and point out difficulties rather than the analysis of large data sets.

GLOBAL CAPABILITIES

PMI far exceeds the other two techniques in spatial coverage of the model since the wing shape can be measured over the entire field-of-view. Deformation data from PMI are available as images of the model that can be interrogated at any location to determine streamwise or spanwise deformation. The density of targets that can be applied to a model for the VMD and Optotrak™ approaches is limited in the streamwise and spanwise directions by the requirement that targets must be distinct without possibility of target confusion. In addition, the installation of Optotrak™ IRED targets within a narrow wing surface can be a major consideration. Current software limitations for VMD restrict the number of target rows in the spanwise direction to 11 or less and the total number of targets to 121 or less. Typically at the NTF, four spanwise target rows are used. Five or more rows are sometimes used at the NASA Langley UPWT and other facilities. For many of the nearly solid metal models tested such coverage is often deemed sufficient since the twist and bending induced by aerodynamic loading is sufficiently well behaved to allow for interpolation between target rows if desired. For models with spar and rib interior construction and aluminum skins the spanwise or chordwise aerodynamically induced deformation may not be as well behaved. For such wings PMI offers definite advantages over VMD and Optotrak™ as discussed in more detail in reference 18.

INSTRUMENTATION UNIFICATION

The number of optical techniques that may potentially be used during a given wind tunnel test is continually growing. These include parameter sensitive paints that are sensitive to temperature or pressure, several different types of off-body and on-body flow visualization techniques, optical angle-of-attack, optical measurement of model deformation, optical techniques for determining density or velocity, and spectroscopic techniques for determining various flow field parameters. Often in the past the various optical techniques were developed independently of each other, with little or no consideration for other techniques that might also be used during a given test. Part of the justification for this approach was that many of the measurement attempts with optical techniques were for demonstration or proof-of-concept purposes rather than for routine measurements[19]. In order not to compromise wind tunnel productivity, the techniques selected for a given test should ideally work together in a seamless and unified manner so as not to require separate run series. However, unified instrumentation does not necessarily mean that common cameras or data acquisition systems are employed for the various techniques. Such attempts at creating a hybrid measurement system often result in an awkward system that is not well suited for practical use. Rather what is meant by unification is a cooperative interaction where all needed measurements are obtained without appreciable interference between the techniques.

In addition to concerns about productivity, there are only a limited number of viewing and lighting window-ports that must be shared by the various optical techniques in a production wind tunnel. Perhaps even more crucial are conflicting requirements for the various techniques. For example, one technique may require that the test section lights be turned off, interfering with model surveillance as well as other techniques that require the test section lights be on. It is expected that the issues of unified instrumentation will become increasingly important in the future due to the major emphasis on productivity and the demand for the use of various optical techniques during production testing.

All three techniques can be used with other techniques to some extent. A discussion of the unification problem with specifics on the combined measurements of PSP and TSP with model deformation can be found in references 20 and 21. The PMI and Optotrak™ systems are relatively independent of lighting used for model surveillance since both techniques work in the infrared and employ visible spectra block filters. When retroreflective targets are used the VMD technique is relatively independent of surveillance lighting. However, when using polished paint targets conflicts can occur since the same lighting is used for target illumination as for surveillance. An additional unification issue has arisen at the NTF since the requirement of a black test section wall for VMD is at odds with a requirement for a retroreflective covering on the wall for a dedicated focusing schlieren system. Table 1 presents the typical operating wavelengths of a number of optical techniques that may potentially be used in a given wind tunnel experiment[3].

PMI has previously been used in a unified manner with DGV and fringe-type laser velocimetry in a rotorcraft test conducted in the 14-by 22-Foot ST, and with VMD for tests in the UPWT and TDT. Future tests using PMI simultaneously with PSP/TSP are anticipated. Investigations are also underway to combine VMD and PMI in order to utilize the best attributes of each technique to provide both high accuracy and global capabilities.

Measurement Technique	Typical Operating Wavelength(s), nm
PMI	800
VMD	Visible
Optotrak™	820
LV(fringe type)	476, 488, 514
DGV	514, 532
PIV	532
PSP/TSP	400 ± 50, 650 ± 50
LITA	532, 750, 1064
IR Thermography	4000 ± 1000
Phosphor Thermography	365, 600 ± 50

Table 1: Optical measurement techniques used in wind tunnel applications with wavelengths.

LIMITATIONS

One of the primary limitations of the VMD single-camera single-view technique, in addition to the requirement for targets, is that one coordinate must be known. This restricts the usefulness of the technique to pitch sweeps only unless additional knowledge about the third coordinate is available or at least one additional video camera is used so that 3D spatial intersection can be used. Another limitation of the VMD single-camera approach is that typically the spanwise coordinate (designated by *Y*) is assumed constant. However, Y is not constant during wind-on conditions due to possible model yaw dynamics and wing bending. This variation in *Y* contributes to the precision error. Recording and analyzing multiple images to determine mean image coordinates reduces this error due to *Y* by averaging. For rigid body motion the change in Y will be nearly the same for targets that are not too separated in image space. Hence these targets will have nearly equal errors in X and Z that will tend to cancel when angles are computed. The shift of Y due to bending produces a bias error in X and Z. However, targets at the same semispan station will experience similar Y shifts that again will tend to cancel this bias error when angles are computed.

The VMD and Optotrak™ techniques are of limited value for measurements on narrow control surfaces such as leading edge slats that may extend only a little in the chordwise direction since it may be difficult to place sufficiently spaced targets on such surfaces. The IRED targets required by Optotrak™ are much more difficult to place within thin surfaces than externally applied targets and also necessitate additional wiring in the model. For many existing models the installation of IRED targets in the wing surfaces would be impractical. The PMI technique does not suffer target placement limitations, but does require that the surface of interest be diffuse. Highly polished models such as used at the NTF may require that paint be applied, or that PMI data be taken when the model surface is prepared with TSP or PSP. In addition, PMI requires that the surface of interest also be illuminated with a projected grid. Thus PMI (and Optotrak™ as well) must have optical access to the surface of interest from two distinct locations. Wing shapes such as a gull wing can be troublesome to illuminate and view simultaneously. The PMI technique (and to a lesser extent the VMD technique) also may be of limited value when the model undergoes extremes in translation during pitch sweeps such as can occur in facilities without an arcsector pitch arrangement.

OTHER APPLICATIONS

The VMD technique has been used additionally to measure sting bending, study model injection, and to calibrate and validate methods for predicting static aeroelastic deformations of wind tunnel models. VMD has also made 25-second recordings at a 60 Hz rate of pitch changes of an oscillating airfoil as a function of time. Investigations are also underway to assess the usefulness of VMD for model attitude measurements. Initial measurements have also been made with VMD for flap and gap deformation of wind tunnel models. Future tests to assess the relative merit of the VMD technique to measure large structure out-of-plane deformation (such as test section walls) are also planned. In-flight deformation measurements with VMD are also being considered.

The PMI technique has been used for a variety of non-wind tunnel applications at NASA-Langley including characterization of piezoelectric actuators, and the measurement of load-induced out-of-plane deformation of aluminum test specimens under applied compression and tension. PMI was recently used to measure the global deformation of an Active Twist Rotor Blade containing piezoelectric patches which generated blade twist when actuated. Blade twist measurements with ±0.01° accuracy were obtained using a 450-x 450-mm field-of-view PMI system in this laboratory experiment. Deformation measurements of composite bands with interwoven shape memory alloy wires are planned that will be the first time PMI has been used for applications at elevated temperatures.

Optotrak™ has been employed to measure effects on a model's pitch angle due to side-to-side motion of the sting in a laboratory simulation setup. Further wind tunnel tests in the Langley 14- by 22-foot and Transonic Dynamics Tunnels are planned for the near future. Using the RH-2020 system to measure angles (pitch, roll, angle-of-attack) of models in some of Langley's hypersonic facilities is being investigated. Questions of IRED cooling, marker placement in small models, and proper data format have yet to be fully resolved. Interest has also been expressed in dynamic measurements using Optotrak™ that can quantify the movements and deformations of models under test in order to extract frequency information.

IMPLEMENTATION COSTS

The Optotrak™ is the only one of the three techniques that is readily available commercially in a form directed toward wind tunnel usage. However, even for Optotrak™, special software is necessary for some of the specialized angle or displacement measurements required in wind tunnels, as well as for interfacing with the facility data acquisition system. The approximate cost of an Optotrak™ system for wind tunnel use in 1999 is around $160,000. The estimated cost of a commercial single-camera VMD prototype measurement system is around $30,000. The basic hardware for a single-camera VMD system is less than $15,000. Commercially available 3-dimensional vision systems range from $50,000 to $100,000. The basic PMI hardware for a laser-based system is estimated to cost less than $45,000, with non-laser based systems costing considerably less at $20,000. However, for both VMD and PMI, software development is the key to an effective measurement system.

MATURITY

Optotrak™, being a commercial product, is the most mature of the three techniques in general. However the single-camera single-view VMD technique is the most mature technique for wind tunnel model deformation, having been used for many tests at 5 NASA wind tunnels. The single-camera version of VMD was derived from multi-camera wind tunnel work that dates from the mid-1980's. The first demonstrations of the single-camera non-automated VMD method occurred in 1992 with the first limited automated tests occurring in 1994. The first automated tests with VMD at the NTF occurred in 1997. PMI has been investigated by DLR in Germany for the measurement of hinge moments and model deformation[22]. PMI was also selected as a dedicated system to measure model deformation at the European Transonic Wind Tunnel. The LaRC PMI development program began in late 1996, with the first wind tunnel application occurring in the 14- by 22-Foot ST in late 1997.

FUTURE ENHANCEMENTS

Enhancements to the techniques used for the measurement of gap and flap geometry are needed in order to increase the accuracy and utility of the VMD method for such measurements. Efforts are underway to decrease the time required for pre-test calibration to less than one hour so as not to negatively impact facility productivity. It is also desirable to reduce or eliminate the adverse aerodynamic effects of targets used for VMD. Efforts are underway to improve the accuracy of VMD to 0.01° under wind-on conditions and to improve the dynamic capability of the technique to 500 Hz. It has been observed that VMD and PMI can be complementary[18]. The VMD and PMI techniques will be merged to the extent possible in order to take advantage of the higher accuracy of VMD along with the global coverage of PMI. The potential for combined use of the Optotrak™ and PMI will be further considered as well. The merger of the point source IREDs having better accuracy and the global nature of the PMI method are complementary. More powerful diode emitters, laser diodes, and the use of fiber optics present possible improvements in the Optotrak™ range of applicability and accuracy under adverse conditions.

Many of the ongoing PMI system enhancements such as hardware and software improvements of usability and accuracy are described in detail in reference 3. PMI data analysis software will be developed to facilitate easier extraction of quantitative twist and bending values from PMI deformation images. The image processing code will also be time optimized to approach the goal of 3 seconds per image, facilitating near real-time data turnaround. High resolution, progressive scan CCD cameras are being implemented to improve measurement accuracy and resolution, and to greatly increase the conditional sampling capabilities of the PMI system. Improved procedures for instrument calibration will be investigated, with the purpose of achieving higher accuracy calibrations with minimal user interaction.

COMPARISON SUMMARY

A summary of the relative comparisons of the VMD, PMI, and Optotrak™ measurement systems is presented in Table 2 below. For each attribute a rating of 10 is given to the technique that is judged *best.* The relative weight of each attribute is not addressed in the table, thus the highest total rating does not necessarily indicate the technique of choice. For instance critical attributes such as accuracy and cost may be much more important, in some cases, than the other attributes. The overall ranking of the techniques for the several attributes that are most important for a given application may be useful for selecting the *best* technique for a given task.

	VMD	PMI	Optotrak™
Uncertainty	**8**	**4**	**10**
Environmental	**10**	**8**	**8**
Model Configs	**8**	**10**	**10**
# of viewports	**10**	**7**	**7**
Model prep	**10**	**8**	**6**
Calibration	**10**	**10**	**10**
Data acquisition	**8**	**8**	**10**
Data reduction	**8**	**4**	**10**
Data turnaround	**8**	**4**	**10**
Lighting	**7**	**9**	**10**
Global	**6**	**10**	**4**
Unification	**8**	**10**	**10**
Limitations	**6**	**8**	**10**
Other applications	**10**	**10**	**10**
Maturity for Def.	**10**	**8**	**6**
Cost	**10**	**8**	**4**

Table 2. Relative comparison of video photogrammetry (VMD), projection moiré interferometry (PMI), and Optotrak™.

CONCLUDING REMARKS

Each of the three techniques compared here (video photogrammetry, projection moiré interferometry, and the commercially available Optotrak™ system) has advantages for specific applications where model deformation measurements are required. As is often the case, no one technique is best suited for all situations and cost-benefit tradeoffs may be necessary. Developments, improvements, and applications continue for all three techniques. Further wind tunnel comparison experiments using the three techniques are anticipated that should provide additional information regarding appropriate uses of the techniques.

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