AIAA-98-2500
Data Fusion in Wind Tunnel Testing;
Combined Pressure Paint and Model
Deformation Measurements (Invited)

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20th Advanced Measurement & Ground
Testing Meeting
June 15-18, 1998 / Albuquerque, NM

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ABSTRACT

As the benefit-to-cost ratio of advanced optical techniques for wind tunnel measurements such as Video Model Deformation (VMD), Pressure-Sensitive Paint (PSP), and others increases, these techniques are being used more and more often in large-scale "production" type facilities. Further benefits might be achieved if multiple optical techniques could be deployed in a wind tunnel test simultaneously. The present study discusses the problems and benefits of combining VMD and PSP systems. The desirable attributes of useful optical techniques for wind tunnels, including the ability to accommodate the myriad optical techniques available today, are discussed. The VMD and PSP techniques are briefly reviewed. Commonalties and differences between the two techniques are discussed. Recent wind tunnel experiences and problems when combining PSP and VMD are presented, as are suggestions for future developments in combined PSP and deformation measurements.

NOMENCLATURE

P	Surface pressure in test condition
P_r	Surface pressure in reference condition
I	PSP emitted intensity in test condition
A, B	Modified Stern-Volmer coefficients
I_r	PSP emitted intensity in reference condition
X, y	Coordinates of a point in the image plane
X_p, y_p	Image plane coordinates of the principal point

X, Y, Z	Three-dimensional coordinates of a point in space
X_c, Y_c, Z_c	Three-dimensional coordinates of the camera perspective center
$\Delta x, \Delta y$	Systematic errors in the image plane coordinates
m_{ij}	Tensor relating model and image plane coordinates
f	Camera principal distance
$L_1 ... L_{11}$	Direct linear transform coefficients

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INTRODUCTION

The past decade has seen the development of optical instrumentation technologies for wind tunnel applications that show promise for near routine use in large scale production-oriented facilities. Two of these techniques are pressure-sensitive paint (PSP) and video model deformation (VMD). PSP was first developed in the late eighties and early nineties in the United States and former USSR.[1,2] While the advantages of PSP as a flow diagnostic method were appreciated almost immediately, the technique has been largely developed as a replacement for pressure taps, especially for loads estimation on wind tunnel models. Work on PSP has also prompted the development of the almost identical technique of Temperature-Sensitive Paints (TSP). Useful reviews of both topics can be found in references 3 and 4. Development of VMD was initiated in the eighties[5] based on earlier successful wind tunnel tests in the seventies using film cameras.[6] The history of the development of a model deformation measurement capability for the National Transonic Facility is presented in reference 7, which includes the rationale for the current single camera, single view photogrammetric technique, with emphasis on the measurement of the change of wing twist due to aerodynamic load. A major breakthrough for VMD, which allowed near routine use in production wind tunnels, occurred in the mid nineties with the introduction of image processing routines to automate data acquisition and reduction.[8] A recent review of VMD can be found in reference 9.

Some general observations are made regarding desirable attributes of useful test techniques that must

be considered when combining any of the optical techniques. More specific problems encountered when combining VMD and PSP are then discussed. Although a system for combined pressure paint and model deformation measurements is still in its infancy, several combined wind tunnel demonstration experiments have been conducted to date. The main thrust of these demonstration experiments was to investigate the problems associated with simultaneous acquisition of the optical targets used by both PSP and VMD.

DESIRABLE ATTRIBUTES OF USEFUL TEST TECHNIQUES FOR WIND TUNNELS

It has been suggested[10] that for an advanced wind tunnel measurement system to be useful it should (1) provide the right data in the right format, (2) be non-intrusive, (3) be model and tunnel independent, (4) be operable by a non-specialist, and (5) be cost effective. To this list should be added the following: the technique (6) should have sufficient uncertainty to meet test objectives, (7) should not negatively impact productivity, and (8) should be able to accommodate other techniques. Optical techniques for wind tunnel measurements that appear suitable in the laboratory may have to be reworked significantly for use in large production facilities. For this purpose it is often desirable to consider wind tunnels as very large laboratories where instrumentation enhancements and developments should be conducted on as nearly a "non-interference" basis as possible. Many of the challenges associated with the development of useful wind tunnel test techniques are best met by iterating between wind tunnel and laboratory investigations, where the laboratory is used to investigate problems uncovered during the wind tunnel entries and to make improvements in preparation for the next entry.

Optical techniques are usually regarded as non-intrusive (attribute 2), however J. P. Crowder[11] points out that even though optical techniques may be non-intrusive to the flow, they can have a very significant intrusiveness in terms of time, cost, and effort. It is crucial, in order for optical techniques to be useful, that time and effort be reduced for setup time, calibration (before and during the test), model preparation, and special data acquisition requirements. Adequately defining and meeting the uncertainty requirements (attribute 6) is crucial to improving productivity (attribute 7), which is an especially major concern during times of budget reductions. The standard 'polars-per-test' measure of productivity will eventually be replaced with 'knowledge-per-test', which although harder to assess, is a better measure of productivity. Advanced measurement techniques may produce fewer polars-per-

test, but may provide new knowledge that could not be obtained otherwise. The unification of optical techniques (attribute 8) is becoming increasingly important due to the myriad optical techniques available today. By combining paint and model deformation measurements, separate runs would no longer be needed, thus improving productivity in terms of polars-per-test and possibly knowledge-per-test since both techniques will have a higher probability of being used if less runs are required.

When attempting to unify several optical techniques, it is generally best not to put the whole burden of accommodation on a single technique, but rather strive for equal accommodation from each of the techniques. However, there may be situations that require unbalanced accommodation. For reasons described in detail below, the current approach to combining paint and deformation measurements has been to view PSP reference targets with the video deformation camera under the UV illumination used for the paint measurements. The deformation system is adapted to the paint system with little change in the operation of the latter except in the size and number of optical targets used.

Optical techniques can be divided into two categories.[10] In the first category are techniques that exceed conventional instrumentation with greater accuracy, extended range, lower cost, or higher speed. In the second category are techniques that provide new insight or previously unavailable information. The parameter sensitive paints, PSP and TSP, fall in the first category, whereas model deformation measurements fall into the second. A number of separate applications of paint and model deformation measurements have occurred in a variety of large production wind tunnels over the last several years. However, applications of model deformation are not as common in the ground testing community as are applications of paint. Even though both paint and model deformation have progressed from the demonstration stage to the application stage, further developments and enhancements are needed before these techniques are able to meet all the desirable attributes listed above.

DEFORMATION MEASUREMENTS IN WIND TUNNELS

The two primary techniques currently being used, or under study, for the measurement of deformation in wind tunnels are video photogrammetry (also known as video model deformation or VMD) and projection moirÈ interferometry (PMI). Both techniques have benefited from the rapid advancement in the

American Institute of Aeronautics and Astronautics

development of video CCD cameras and computers. The VMD approach is more mature than the PMI approach for production wind tunnel, testing having been used in nearly 20 wind tunnel tests at 5 NASA facilities since January 1996. The PMI approach under development at NASA Langley has been used for 2 recent tests at NASA facilities,[12] but is not ready for production testing. (The PMI system under development by DLR for the European Transonic Wind Tunnel (ETW) may also not be ready for production testing.) Improvements and enhancements to both approaches are still underway. Some of the limitations of VMD, not suffered by PMI, are: (1) data is limited to alpha sweeps only, (2) targets must be applied, and (3) reduced data is only available at discrete locations where targets are located. However, PMI systems require 2 window ports (for the projector and camera) whereas the VMD system only requires one port Also while both approaches have rapid data acquisition, VMD has much faster data reduction than PMI at present, with near real time reduction of angles and rapid (in minutes) reduction for twist and bending once wind-off polars are completed. It is sometimes necessary to apply flat paint on regions of the model for both techniques, where glints obscure targets for VMD, or to provide a sufficiently diffuse surface for PMI. The discussion of combining paint and deformation measurements in this paper is restricted to the VMD technique due to its maturity for production testing.

Video Model Deformation (VMD) Technique
The video model deformation (VMD) technique consists of a single camera, single view, photogrammetric solution from digital images of targets placed on the wing at known semispan locations. 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, light source usually located as close to the camera as possible (for all facilities except the National Transonic Facility), frame grabber board, and computer with image acquisition and reduction software. The camera is set up to the side and somewhat above the model, so as to view the wing at an oblique angle. Targets are typically placed on or near the fuselage to serve as control in addition to the targets at known semispan locations along the wing. Flat black paint is sometimes used to remove glints and increase target contrast. 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 (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. Figure 1 shows a flowchart of the VMD system's data acquisition/reduction path. Once the VMD system is set up, it waits until a signal is received from the wind tunnel. Images are then acquired and processed as described above. Note that since the VMD system is always assumed to take data faster than the wind tunnel data system, interaction between the wind tunnel and the VMD system can be kept very simple.

The resolution of the deformation measurement system 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 angle-of-attack tests using body targets indicate that 0.01° resolution can be achieved during wind-off tests and is possible for wind-on tests, provided that the target row(s) occupy nearly the entire image plane and 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 the 25% since the camera must also image the inboard portions of the wing and body. Thus a typical angular resolution for model deformation measurements may be 0.05° or worse near the wing tip due to the small fraction of the image plane occupied by the row of targets at the tip.

The resolution of the deformation system decreases as the angle of incidence to the wing surface increases. A conflicting requirement arises due to the use of retroreflective tape targets since the light return falls off very rapidly past an angle of incidence of 45° such as occurs when viewing the wing at a shallow angle for increased resolution. Thus to ensure adequate light levels on the image plane it may be necessary to increase the angle of incidence at the expense of angular resolution. Another complication, simply based on geometry, is that the angle of incidence will vary across the wing surface, causing a marked variation in image plane illumination in addition to a varying resolution in the spanwise direction.

NASA Facilities with Deformation Measurement Capability
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. A number of deformation measurements have been made on various models at all 5 of these facilities, including sting mounted and post mounted full span models in addition to sidewall and floor mounted semispan models. While each of these facilities presents unique challenges to the installation of measurement systems, the most difficult instrumentation challenges occur at the NTF. There, constraints imposed by operation in a high-pressure environment over a wide temperature range (+140 to -250 F) have had a significant impact on the continuing development, improvement, and optimization of instrumentation at the facility (particularly for the measurement of model deformation). For example, retroreflective tape targets have not yet been used at the NTF as in the other 4 facilities due to concerns about the aerodynamic effects due to target thickness and difficulties in locating a light source sufficiently close to the VMD camera. Thus a special polished paint technique for targets has been developed and investigations continue on improved targeting schemes for the NTF that may also be advantageous at other facilities.

Target Developments for VMD

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. A calibration cone (Fig 2) has been tested at the National Transonic Facility with a variety of targets including polished paint applied directly to the surface. In addition milled targets have been tested with filler over white paint, retroreflective tape, fluorescent dye and filler mixture, and retroreflective paint. The 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 of 0.004 inch is removed, but the surface roughness can be as large as 200 μinches. Retroreflective tapes with surface roughness down to 20 μinches 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 0.0005 inch with surface roughness of 5 μinches) 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.

PRESSURE- AND TEMPERATURE-SENSITIVE PAINT MEASUREMENTS IN WIND TUNNELS

Pressure-Sensitive Paint (PSP) Technique

The PSP system most often used at Ames employs scientific grade, slow scan CCD cameras to image model surfaces which are illuminated with continuous UV light. PSP data acquisition often requires a large amount of time relative to conventional wind tunnel instrumentation. This is especially true in low speed wind tunnels, where many images must be averaged in order to achieve acceptable signal to noise ratios. In order to make the most efficient use of test time, PSP data acquisition follows the flowchart shown in figure 3. A specialized software application called SERVIO, acts as a buffer between the wind tunnel and the PSP system. SERVIO is designed to allow one or more independent instrumentation systems to interact with the wind tunnel's conventional data acquisition system (DAS). SERVIO gives unconventional systems a simple, single interface through which they can coordinate their activities with the DAS while receiving tunnel condition data from it.

The PSP technique most often used at Ames is an intensity-based measurement using either single- or bi-luminophore paints. Figure 4 shows a flowchart of the data reduction procedure for the single luminophore method. Images of the wind tunnel model are taken in both the wind-on test condition and a wind-off reference condition. Each wind-on image must be matched to a wind-off image taken at the same model attitude and configuration. A ratioed image is then formed by dividing the wind-off image by the wind-on image on a pixel-by-pixel basis, after registering the wind-on image to account for model deformation due to airloads. Points on the image are related to the corresponding points on the model by means of a colinearity equation. Both this technique as well as the image registration method are described in reference 13. The ratioed image intensity is assumed to be to the model surface pressure via a modified Stern-Volmer relationship[2], so that

$$\frac{I_r}{I} = A + B\frac{p}{p_r} \qquad (1)$$

Here A and B are constants most commonly determined by *in situ* calibration. This is done by relating pressure data obtained with conventional pressure taps to the intensity ratio data at the tap locations, using a colinearity relation to find the tap positions on the image. A least-squares fit is used to find A and B. An alternative is to use the *a priori* calibration technique, where A and B are determined from a test coupon in a calibration cell. Although this technique has also been applied, it is less mature than the *in situ* method. Once the calibrated image has been obtained, colinearity is once again used to map the image data onto a model surface grid.

In the biluminophore method, side-by-side cameras are used to image a paint that contains both a pressure-sensitive luminophore and a pressure-insensitive reference luminophore. The intent of the second luminophore is to provide a constantly available reference source which can be used in place of the wind-off image. While the use of a reference luminophore introduces several complexities in data reduction, it does not have any significant effect on the interaction between the PSP and VMD systems.

For PSP systems, both spatial resolution and pressure resolution are of interest. The current Ames PSP system uses 1024x1024 pixel CCD cameras, giving a maximum spatial resolution of one part in 1000 of the field of view. Pressure resolution is determined by the grey scale resolution of the CCD camera and the pressure sensitivity of the paint. Dark image subtraction and flat field ratioing are used to reduce the effects of fixed pattern noise (nonuniformity independent of irradiance) and responsivity variations (nonuniformity dependent on irradiance) for each pixel across the array. For reasonable exposures the ultimate determinant of a camera's grey scale resolution is photon shot noise.[14] Thus the limiting grey scale signal to noise ratio is the square root of the number of photons received on the detector, and is thus proportional to the square of the exposure time. One result of this fact is that high pressure sensitivity of the paint itself is not always desirable, because of the negative correlation between paint brightness and pressure. Given two paints with equal brightness under vacuum conditions, the more sensitive paint will be dimmer at pressure, and longer exposure times will therefore be required to obtain the same grey scale resolution. Another consequence of shot noise limitations is that a PSP camera with high video frame rates cannot achieve higher precision

through frame averaging; the mean of 10 images each containing 10,000 photon/pixel is no more precise than a single image containing 10,000 photons/pixel.

When data from pressure taps are available, one common measure of PSP accuracy is to find the RMS difference between pressure measurements taken with taps and the PSP measurements at the tap locations. Accuracies of .02 in C_p units, as defined by this measure, are readily obtainable in transonic testing. At low subsonic speeds ($M = 0.1$-0.2), accuracies of 0.1 to 0.2 are more typical, although accuracies of 0.05 can be achieved if the facility is carefully controlled. In small scale, research facilities, accuracies of 0.02 in C_p have been achieved at speeds as low as $M = 0.1$.

NASA Facilities with PSP and TSP Capability
PSP or TSP measurement systems have been successfully operated in a large number of NASA facilities. At Ames these include the 11-Foot Transonic Wind Tunnel, 9x7-Foot Supersonic Wind Tunnel, 12-Foot Pressure Wind Tunnel, 40x80-Foot Wind Tunnel, 14-Foot Transonic Tunnel, and 7x10 Foot Wind Tunnel. At Langley, the 16-Foot Transonic Tunnel, Unitary Plan Wind Tunnel, 14x22 Foot Tunnel and the BART have all used PSP. TSP measurements have been made in the National Transonic Facility at Langley. At Lewis, PSP has been used in the 10x10 and 8x6 Supersonic Wind Tunnels, the 9x15 Low Speed Wind Tunnel, and the Icing Research Tunnel, as well as a large number of smaller test facilities. In contrast to VMD systems, PSP hardware is sufficiently expensive that a dedicated system for each facility is not practical at this time. Instead a pool of PSP hardware is maintained to cover the needs of testing in the different facilities. Each facility poses unique problems for the PSP technique. These range from very long sight distances and subsequent large illumination requirements in the 40x80-Foot Wind Tunnel, to 6 atm operating pressures in the 12-Foot Pressure Tunnel, to high temperature and vibration loads in the 14-Foot and 16-Foot Transonic Tunnels. The cryogenic nitrogen operating environment of the NTF poses an extraordinary challenge to PSP measurements, which are only now being addressed,[15] although TSP measurements have been successful in this and other NASA cryogenic facilities.[16]

PSP AND VMD SYSTEMS COMPARED

PSP and VMD are similar in that both use video cameras to acquire data from the specially-prepared surface of a model which is illuminated by a controlled

light source. A more careful examination of the technologies reveals numerous incompatibilities, which must be reconciled if the two systems are to be combined.

Camera Requirements

The primary requirement for a PSP camera is high grey scale resolution, whereas the model deformation system is primarily concerned with spatial measurements on the camera image plane. For a typical pressure-sensitive paint, a system which resolves a C_p difference of 0.01 at transonic speeds might require a camera with an SNR of 500:1.[17] Since standard RS-170 format video cameras are not capable of this resolution, most PSP systems use specialized scientific grade video cameras. In its normal mode of operation, without combining with PSP, the VMD system views high contrast, high light level targets, so that a scientific grade CCD is not needed. Thus it is common to use RS-170 format video grade (60 field per sec) cameras for model deformation. Investigations using scientific CCD cameras with high contrast targets during which various levels of gray scale from the same digital images are use to compute centroids indicate little change in centroid location beyond 8 bit gray scale resolution.[18] However, when using paint UV illumination the PSP reference targets appear low contrast and are at a low light level for the video CCD camera, causing the centroid operation to be marginal. Thus it may be desirable to consider scientific grade CCD's for the deformation measurements when attempting to combine the two techniques using UV illumination only, even if the capability for multiple frames must be sacrificed.

High spatial resolution video cameras are more important to VMD systems than to PSP. All other things being equal, increased spatial resolution directly increases the accuracy of a VMD measurement. In contrast, a PSP system using even a modest video camera has far greater spatial resolution than conventional pressure measurement techniques. Oddly enough, the PSP system described in this report has greater spatial resolution than the VMD system. This has happened because of VMD's use of RS-170 format video cameras, which are limited to about 752x480 pixel resolution per frame (or 752x240 per field). This spatial resolution is acceptable for VMD work. Although resolution much above, say, 500x500 pixels is unnecessary for most PSP applications, paint systems tend to use large area CCDs in order collect as many photons as possible in a single image. Large area CCDs almost inevitably have high spatial resolution, and so PSP systems achieve this capability as a by-product.

Video CCD cameras not only cost less, but enable the recording of multiple fields of image data per data point. The recording of multiple fields is especially important in dynamic situations such as occur near the onset of buffet. Averaging the results from multiple frames also reduces the error in the mean pitch angle due to motion in the yaw plane. Finally, since targets do not move by a large amount between successive video fields, it is relatively simple to set up target tracking software, which allows the system to automatically track a target on the image after initial identification by an operator. Recently pixel clock synchronization of the frame gabber has been investigated for wind tunnel applications to improve the spatial stability of video CCD cameras. PSP systems, however, have relatively less to gain from fast imaging rates. To be useful for dynamic measurements, a fast camera would also have to be accompanied by a fast time response paint, as well as a light source bright enough to generate enough emitted photons to resolve the paint's pressure signal in a short period of time.

PSP and VMD systems prefer significantly different viewing angles. PSP cameras are typically positioned for a normal view of the model that maximizes spatial resolution, presents a view of the model that is least confusing to the viewer, and minimizes the depth of field required to keep the entire model in focus. Since the grey scale resolution of the camera is related to the number of photons it can collect, it is desirable to operate PSP cameras with as large an aperture as practical, with a concomitant loss of depth of field. VMD cameras are typically mounted so as to obtain an oblique view of the model, since doing so increases the camera's sensitivity to small motions in the Z direction.

Lighting Requirements

VMD systems work best with a special illumination system, whereas PSP absolutely requires one. For a VMD system, it is desirable to illuminate the model with a strong light source mounted near the camera. This will brightly illuminate the retroreflective targets, while the oblique viewing angle of the lamp, together with the judicious use of flat black paint, insures that the remainder of the model is relatively dim. Since the CCD camera is sensitive to a wide variety of wavelengths, the spectral characteristics of the lamp are not significant.

Lamps for illuminating PSP, on the other hand, must have spectral characteristics that are consistent with the paint itself. That is, the lamp must have high brightness at the excitation frequency of the paint, and little or no emission at the emission frequency of the paint. When

the wind-off / wind-on technique is used, it is also desirable that the lamp output be very stable, since any change in lamp output is sensed as a change in pressure. These comments also apply with respect to flash-to-flash variation if a flash lamp is used to illuminate the paint. Lamp drift is less significant when *in situ* calibration is used and the model is illuminated from a single point source. The *in situ* calibration process factors out changes in mean illumination, and changes in a single point source affect all parts of the model proportionately. It is often the case, however, that the model is illuminated from several different directions to obtain an even illumination field. In this case any intensity fluctuation in a single lamp is a significant error source. When illuminating a PSP, it is desirable to have the illumination source as close to normal to the model surface as possible. This minimizes the change in surface illumination that occurs when the model moves or deforms under aerodynamic loads. (Although the use of biluminophore paints can substantially correct for the error due to this effect.)

Model Surface Requirements

The model surface preparation associated with PSP is essentially incompatible with the usual model surface treatment for VMD. Ideally, VMD would have a black model with the exception of the retroreflective targets. PSP must cover the model with paint, with the exception of black target dots used for a spatial reference. Fortunately, there is no insurmountable barrier which prevents VMD systems from using the same type of black-on-white targets employed by PSP. However, the question as to whether or not the VMD system can locate PSP-style targets with sufficient accuracy remains open.

Assuming that PSP and VMD can make use of the same targets, the question arises as to what are the differences in optimal target placement for the two techniques. In a typical VMD application, chordwise rows of targets are placed at several different spanwise stations on the model wing. The larger a target is in the image, the more accurately its position can be determined. Experience has shown that targets should be about 6-8 pixels across to be located with sufficient accuracy for deformation measurements. Since the model is viewed obliquely, targets far from the camera must be physically larger than nearer targets. PSP uses targets for two different purposes; to register wind-on to wind-off images so as to correct for model deformation, and as calibration points to establish a mapping between physical and image coordinates. Both purposes require that targets be evenly distributed over the model surface. Targets should also be placed near the edges of

the model (as it is viewed by the camera), so that image registration and mapping interpolate between known points as much as possible. Large targets obscure area which could otherwise be covered with paint; this drives down the optimum size of PSP targets compared with VMD targets. For PSP, 4-6 pixels is considered optimum. Target placement and size requirements for PSP and VMD are sufficiently similar that a compromise target set can probably be reached which will satisfy the needs of both techniques.

RECONCILING VMD AND PSP REQUIREMENTS

The requirements stated in the previous section make it difficult to imagine a combined VMD/PSP data system. Many of these requirements, however, can be relaxed in practice.

Camera Requirements

The simplest way to reconcile the VMD and PSP camera requirements is to use separate cameras for VMD and PSP. The RS-170 camera and associated framegrabber used by the VMD system is quite inexpensive compared to the scientific grade still video cameras used by the PSP system. Therefore it is not unreasonable to maintain both cameras in a combined system. However, it is not clear that an RS-170 camera will be able to resolve PSP-style targets with sufficient accuracy, and it would be useful to have this capability. Also, a combined system would be simplified by standardizing on a single camera type. One option is to simply use PSP cameras for VMD, since with the exception of fast imaging rate, VMD camera performance characteristics are a subset of those for PSP. Loss of fast imaging rates compromises the ability of the VMD system to obtain time resolved data., Also, frame-to-frame tracking of targets becomes less practical, since a slower frame rate allows greater motion of the targets from one image to the next. This is not a serious loss of capability if only time-invariant data is desired. However is would be best if fast (up to 30 Hz) imaging rates were included in the camera requirements for a combined system. It is not uncommon for scientific grade cameras to have a so-called focusing mode, in which the camera can output data at video rates, albeit with degraded grey scale resolution. Such a camera could be set up for either PSP or VMD data acquisition. A worthwhile eventual goal would be a camera with sufficient grey scale resolution even in its fast mode to be capable of obtaining PSP and VMD data simultaneously. Even camera placement requirements would not be a great problem, since a camera set up in an optimal viewing position for VMD

measurements would still provide useful PSP images of the side of the model.

Lighting Requirements

A simple method for combining PSP and VMD lighting systems to again observe that the VMD lighting system is relatively cheap, and there is little extra effort involved in installing it alongside the specialized PSP lamps in a combined system. The VMD lamps can simply be turned off whenever PSP measurements are desired. In practice, this method has several drawbacks. It means that measurements cannot be made in a truly simultaneous fashion, and unless the lamps are coordinated by a reliable automated system, there is always the chance that the VMD lamps will be left on, contaminating the PSP data. It is more effective to develop a lighting system that works well for both VMD and PSP. Such a system might work for VMD in one of two different ways. The first is for the VMD camera to sense reflected light in the PSP excitation wavelength. This is reasonable when the paint being used is excited by blue light, but not, as is often the case, when the paint is excited by ultraviolet, since few types of CCD are sensitive to UV. In this case it is still possible to use retroreflective targets for VMD, since the painted surface will strongly absorb the paint excitation wavelength. The second method is for the camera to sense the light emitted by the PSP. In this case, the use of retroreflective targets is impractical, and this method can only work if black-on-white targets can be located with the same precision as white-on-black targets.

Model Surface Requirements

The simplest way to deal with competing surface treatment requirements of PSP and VMD is to allocate each method to a different part of the model. This works well for symmetric models at zero yaw angle, with PSP taking one side of the model and VMD using the other. Another possibility is available when PSP is only desired for flow diagnostics on the upper surface of the model, where the most significant pressure variations often take place. This is to set up the VMD system to image the model's lower surface, which must deform with the same twist and bending angles as the upper surface. However, it is clear that the full potential of both PSP and VMD can be realized only when they can be freely combined on the same surface. This can be done by setting up the VMD system for black-on-white targets. VMD would place large (6-8 pixel) targets on the model as required. Small (4-6 pixel) targets would then be placed in any other areas where they were needed by the PSP system. Figure 6 schematically illustrates the different target pattern favored by the two methods and how they might be combined.
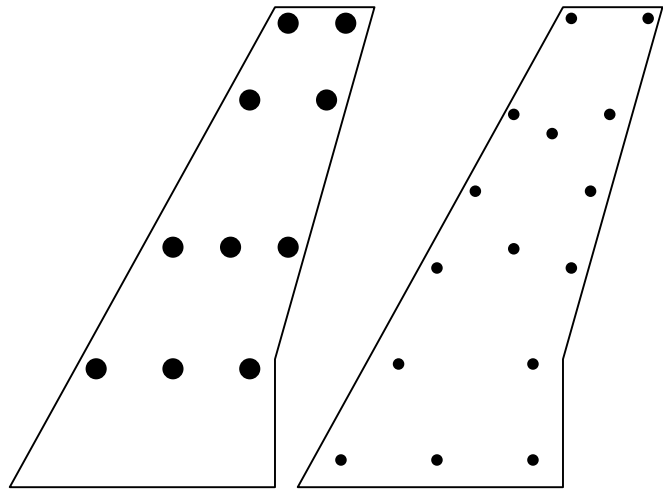

Figure 6a,b. Sketch showing typical target placement on a wing model for VMD (a, left) and PSP (b, right).
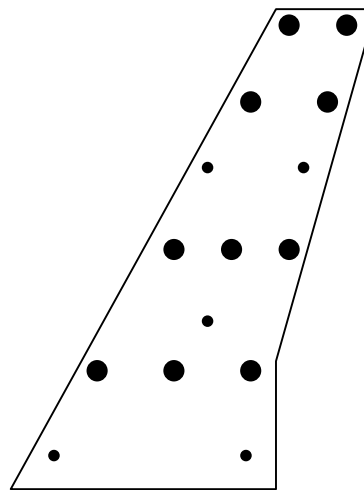

Figure 6c. Typical target placement for combined VMD/PSP system. All VMD targets are retained, and supplemented with smaller targets where needed by PSP.

Combined Data Acquisition

Once the PSP and VMD systems have been modified to operate simultaneously, using compatible if not identical hardware, it remains to merge the data acquisition systems. The data acquisition flowchart for a combined system is shown in figure 7. Note that two key features of the original systems have been retained. First, it is assumed that data acquisition will be slow enough that substantial handshaking will be required

between the wind tunnel DAS and the combined PSP/VMD system. Second, the VMD part of the combined system is still fast enough to do a substantial part of its data reduction while each data point is taken. Some of this capability is extended to the PSP side of the system, by using VMD's procedures to find the target locations in the PSP images, as well as to find the colinearity constants needed by PSP for image mapping. How a combined system might do these things is taken up in the next section, on data reduction.

COMBINED VMD AND PSP DATA REDUCTION

Once PSP and VMD data acquisition systems have been successfully combined, it makes sense to look for advantages which might be gained by combining PSP and VMD data reduction. These advantages exist because some aspects of VMD and PSP data reduction are very similar. Both techniques must accurately and automatically locate targets in the data image. The image locations of these targets are then related to their actual locations in the model coordinate system. VMD uses these data to track target motion in the model coordinate system, while PSP uses them to map image data onto a model surface grid, but the tasks of locating targets and relating the image and model coordinate systems are substantially similar between techniques. By looking at how data reduction techniques developed for one method might help the other, the performance of both systems might be improved.

Paint measurements are much more image processing intensive than deformation measurements. Paint applications typically involve the recording of digital images for later processing by a specialist. Although some PSP experiments have successfully demonstrated near real-time data reduction (40 sec/data point), in most cases fully reduced data may not be available until many days after the completion of the test. The video model deformation approach only makes use of image processing for blob analysis to locate targets, simple threshold removal, and centroiding to determine image plane coordinates in pixels. The technique is therefore more amenable to on-line data reduction. 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 versions of the deformation measurement systems 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 the standard tunnel data. A more efficient procedure under development is to transfer to DAS as each data point is taken the computed slope angles and Z-intercepts for each row of targets at the various semispan stations. The DAS then will compute the twist and bending at the conclusion of a set of runs after the proper wind-off runs to be used are designated, in a manner much like flow angularity might be computed. This procedure will eliminate much of the book-keeping now required of the deformation acquisition system, reduce the amount of required interaction with DAS, may also eliminate the need for a specialist for data reduction, and ensure that reduced deformation data is available with the rest of the standard wind tunnel data in a uniform manner.

Target Location Techniques
The task of automatically locating targets in VMD and PSP images can be divided into three parts. The target positions must first be coarsely determined to an accuracy of a few pixels. Then the target locations must be found to much finer accuracy, typically less than 0.1 pixels. Finally, the targets must be identified, so that each target located in the image can be matched with the model space coordinates stored for that target. Note that target identification can occur after the targets are coarsely located, instead of after fine location.

VMD uses a blob-finding technique to accomplish coarse location, by isolating in the image all pixels which are associated with white dots of a certain size and shape. This procedure is generally accurate at separating the targets in the image from non-target features which appear similar. Since the VMD camera is generally set up to obliquely view a set of chordwise rows of targets on a model wing, the targets will be generally ordered into a series of rows on the image. The blobs on the image are ordered into rows, following information provided by the operator on the number and size of each target. This allows the VMD system to identify which blob is associated with which particular target. Finally, centroiding is used to locate the targets with a typical accuracy of 0.01 pixels.

The PSP target location procedure begins with the operator inspecting a reference image, and coarsely locating and identifying all the visible targets. A centroiding algorithm is then used for fine location of the targets to an accuracy of about 0.1 pixels. In order to locate the targets in test image, the reference image is used as a template. Using a target position in the reference image as a starting point, the PSP system searches the test image for the target. It does this by taking the pixels surrounding the target in the reference image as a template. This template is moved around on

the test image until the point of highest correlation is found. This is presumed to be the target's new location in the test image. Once all targets are found in the test image, it can in turn be used as a reference to locate targets in other images.

In general, VMD target location techniques are more automated and reliable than those for PSP. A major reason for this is that the VMD operator can usually prepare the model surface, and adjust the lighting, so that targets appear very clearly on the image, while other surface features do not. The PSP system operator has less flexibility, since the system must extract data from the (painted) non-target portions of the model surface. In addition, during operation and model changes, scuff, dings, and holes inevitably appear in the PSP surface which cannot be easily distinguished from targets.

One combined approach is to use the PSP technique of an initial identification of targets followed by VMD-style blob-finding and centroiding techniques. Blob-finding appears to be inherently more flexible than the template technique used by PSP. Since an initial list of target positions is provided by the operator, blob-finding can be limited to near those areas, reducing the rate of false targets substantially. In cases where the model has a large range of motion in the image, the nearest previous image can be used as a source of target locations for blob-finding.

Photogrammetry
Spatial image plane calibrations are important for both paint and deformation measurements. In both cases the coefficients of a colinearity relation must be obtained in order to relate image and model coordinates. In the VMD system, the relation to be solved is,

$$x - x_p + \Delta x = - f \frac{m_{11}(X - X_c) + m_{12}(Y - Y_c) + m_{13}(Z - Z_c)}{m_{31}(X - X_c) + m_{32}(Y - Y_c) + m_{33}(Z - Z_c)}$$

$$(2)$$

$$y - y_p + \Delta y = - f \frac{m_{21}(X - X_c) + m_{22}(Y - Y_c) + m_{23}(Z - Z_c)}{m_{31}(X - X_c) + m_{32}(Y - Y_c) + m_{33}(Z - Z_c)}$$

where x, y are coordinates in the image plane, $X, Y, Z,$ are model coordinates, X_c, Y_c, Z_c are the coordinates of the camera, m_{ij} are the coefficients of a tensor relating the two coordinate systems, and f is the camera principal distance. Additionally, x_p, y_p are the coordinates of the perspective center and $\Delta x, \Delta y$ represent additional terms included to model lens distortion. Typically several radial distortion terms and 2 asymmetrical terms are computed. Additional image

plane calibration coefficients include the photogrammetric principal point and principal distance, point of symmetry for distortion, and horizontal and vertical effective pixel spacing. The image plane calibration for the deformation camera makes use of a calibration plate with known target locations. As shown in figure 8, the calibration plate is set up in front of the model to supply a set of targets whose location is very accurately known. While complex, this procedure yields very accurate results. One drawback to it is that an initial guess for the system parameters, including the camera position and orientation, is required for the solution.

PSP uses a similar but simpler approach to spatial calibrations. Target locations on the model surface are first determined by direct measurement. For a given wind-off image, target locations in the image coordinate system are then related to the model coordinate system using the Direct Linear Transform method described in reference 13. In this method, lens distortion terms are ignored, and the colinearity equations to be solved are linearized to obtain

$$x = \frac{L_1 X + L_2 Y + L_3 Z + L_4}{L_9 X + L_{10} Y + L_{11} Z + 1}$$

$$(3)$$

$$y = \frac{L_5 X + L_6 Y + L_7 Z + L_8}{L_9 X + L_{10} Y + L_{11} Z + 1}$$

where $L_1, \dots L_{11}$ are abstract coefficients. In contrast to the method used by VMD, the DLT method does not require an initial guess for the camera coordinates, and is simpler to implement. However the precision of the DLT method is lower, and it is less versatile. In the DLT method, camera external and internal parameters cannot be separated. Thus, unlike VMD, PSP cannot take advantage of laboratory calibration techniques for camera lens parameters, nor can data from multiple camera positions be combined.

Ideally, photogrammetry for a PSP/VMD system would combine the best of both methods. For example, the DLT method used by PSP has been used to automatically generate an initial guess for the VMD camera location, simplifying this part of the VMD camera calibration process. Contrariwise, the accuracy of the PSP system's image mapping can be improved under some circumstances by adopting the VMD system's colinearity equations, as well as by more accurate locating of the model coordinates of the targets.

The accuracy of a PSP spatial calibrations is estimated by using the targets' known locations in model coordinates to calculate their nominal location on the image plane. These are compared to the target's actual image coordinate locations, and the RMS difference between the calculated and actual image coordinates is then used as a measure of the accuracy of the mapping. These image plane residuals are typically fairly constant for a particular PSP camera over the course of a test, and table 1 shows image plane residuals (averaged over the test) for four PSP wind tunnel tests. The accuracy of the mapping technique is sensitive to several different parameters. Tests #1 and #2 are typical of early PSP tests at Ames. Somewhat high image plane residuals are found, independent of the focal length of the camera used. Recently, coordinate measuring arms have been used in the wind tunnel to rapidly and accurately measure target locations once the targets have been applied. For relatively long focal length lenses, as shown by test #3, this improves mapping accuracy dramatically. But this accuracy improvement is lost in test #4, where a shorter focal length lens was used. This is because shorter focal length lenses typically have greater lens distortion, and the DLT equations do not handle lens distortion well. Mapping accuracy improves significantly, however, when the spatial calibration equations developed for VMD, which do include significant distortion correction terms, are implemented in the PSP system.

Test No.	Res-idual	Map-ping Method	Lens focal length	Coordinate measuring arm used?
1	1.2	DLT	15 mm	No
2	1.1	DLT	35 mm	No
3	.25	DLT	50 mm	Yes
4	1.2	DLT	24 mm	Yes
4	.29	VMD	24 mm	Yes

Table 1. Mapping accuracy compared for several tests in large facilities.

One additional advantage might be gained by the PSP system as a result of combination with VMD. This is indicated in figure 9, which shows a flowchart of data reduction for a combined VMD/PSP system. Here it is assumed that a common set of photogrammetry algorithms has already determined the image plane/model coordinate relationship in both the VMD and PSP images. With the complete VMD information, another step can be taken. Currently, PSP data are mapped onto the shape which the model assumes with wind off. Although it would be more accurate to present

the data mapped onto the model as it deforms under airloads, this model shape is not available. However, a combined PSP/VMD system should be able to generate the "wind-on" model shape from the VMD measurements of twist and bending.

WIND TUNNEL TESTS

There have been four wind tunnel tests during which at least a small effort was devoted to combining PSP and deformation measurement systems. PSP and deformation systems were set up together at the Langley Unitary Plan Wind Tunnel in early 1997. The deformation system was not significantly sensitive to the UV illumination used for PSP, but the fiber optic illuminator used for the deformation system did affect the PSP data. For this test separate runs for PSP and deformation were made, with the PSP and deformation systems viewing opposite wings. For the PSP runs the fiber optic illuminator was turned off. Thus, while not simultaneous acquisition, runs for these advanced instrumentation systems could at least be grouped together and taken during the same time period back-to-back, which was considered to be an enhancement. The first simultaneous acquisition of PSP and deformation data occurred at the Ames 12-Ft Pressure Tunnel. A version of the VMD system developed by the High Technology Corporation (HTC) was used to acquire and analyze deformation data with the usual retroreflective targets. This developmental deformation system, which employs continuous target tracking unlike earlier versions, has improved data acquisition robustness in some cases, especially for low contrast targets. For a portion of the test, the HTC deformation system was used to track PSP reference targets. It was found that PSP targets illuminated with standard test section lighting could be tracked, but that targets illuminated with UV could not be reliably tracked. Follow-up tests in which the HTC deformation system was used to track PSP targets were also conducted at the Langley 16-Ft Transonic Tunnel and Unitary Plan Wind Tunnel with similar results. For the 16-Ft test a 0.95 f-number lens was used to provide a higher light level to the camera. In one phase of the Unitary test, projection moirÈ interferometry (PMI) was also used to measure deformation simultaneously with the non-tracking NASA Langley version of VMD. In addition, Doppler global velocimetry (DGV) data were taken simultaneously with the PMI and VMD data (no PSP data were taken for this phase of the test). In summary, with current experimental arrangements, target tracking on PSP reference targets with UV illumination only is

marginal and may not be robust enough for production testing.

The UV illumination for the above tests was continuous. Pulsed UV illumination would allow for more peak power, but the advantage of multiple image recordings for the deformation system would be compromised unless a synchronized strobe were used. Another approach, yet to be tried, is to replace the usual black PSP reference targets with retroreflective tape targets. The retroreflective targets will then appear black to the PSP system so long as the UV illuminator is not close to the cameras. The UV illumination could then be continuous while the light source for the deformation system is turned on and off automatically by trigger for a second or so at each data point to record deformation data. Thus the PSP and deformation systems may be able to acquire data during the same runs with little additional time compared to separate runs, almost as if the data had been taken simultaneously.

CONCLUSIONS

Significant work must still be done before a combined PSP/VMD system can be put into routine operation. However, it is clear that the two measurement techniques are by no means incompatible. The benefit of a combined system would be twofold; first, the simultaneous acquisition of data now obtained sequentially, and second, improvements in the accuracy of both techniques through the exploitation of common features.

As implemented now, VMD and PSP use incompatible cameras, lamps, and surface treatments. Basic similarities between the techniques exist, however, because both methods obtain position data by tracking optical targets fixed on the model. This fact implies a set of common functions (target location and identification, relating model and image coordinates through colinearity) which both techniques must employ. By looking at how these common functions can be combined, we are able to develop a firm framework for a combined system capable of all the standard PSP and VMD functions.

The experience of PSP and VMD provides a guide for how other optical systems might be combined. One common aspect to all imaging systems (DGV, PIV, minitufts, as well as various oil flow and liquid crystal techniques) is that some means must be found to convert the image plane data generated by the instrumentation into the model coordinate system. Photogrammetry in some form or other is the natural technique to accomplish this transformation. Another common thread is the storage and display of complex image data. By focusing on these common elements first, the task of generating a combined system can be simplified significantly.

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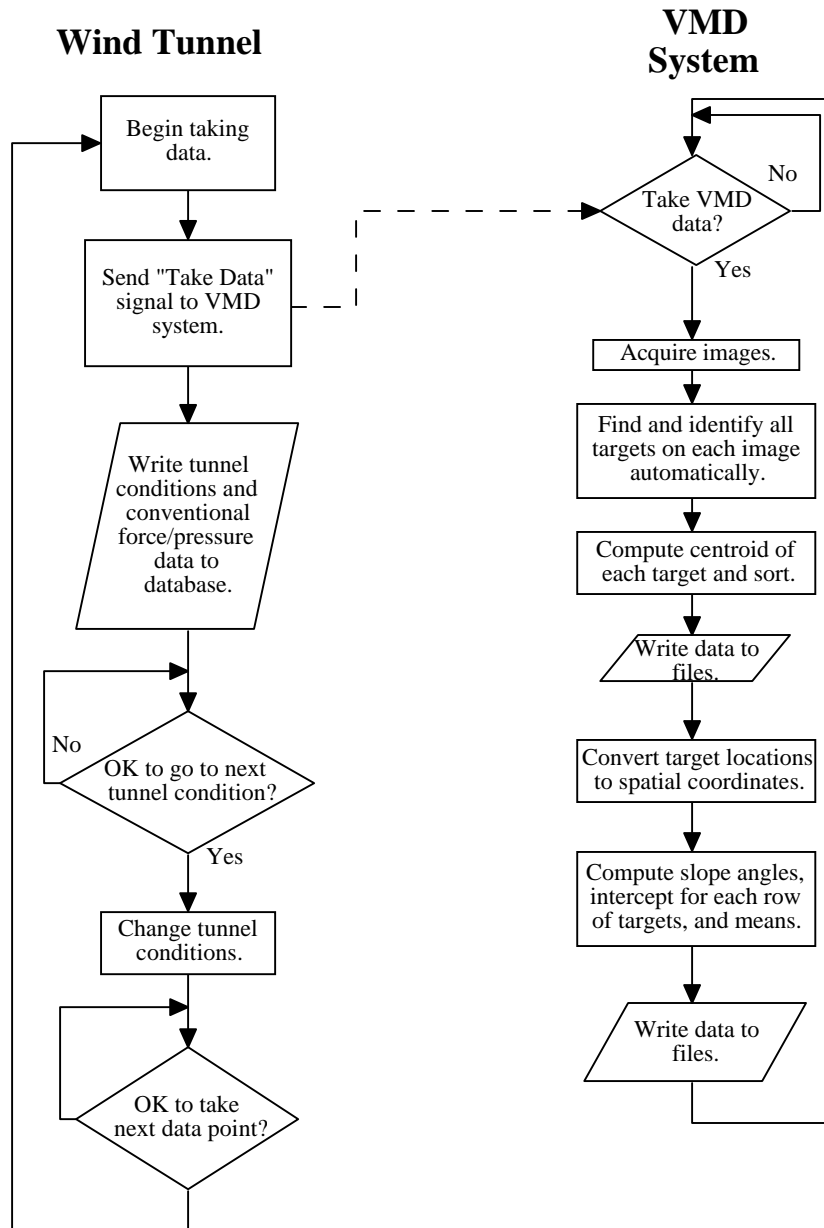
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Figure 1. VMD Data Acquisition Flowchart

Wind Tunnel

VMD System

Begin taking data.

Send "Take Data" signal to VMD system.

Write tunnel conditions and conventional force/pressure data to database.

OK to go to next tunnel condition?
No / Yes

Change tunnel conditions.

OK to take next data point?

Take VMD data?
No / Yes

Acquire images.

Find and identify all targets on each image automatically.

Compute centroid of each target and sort.

Write data to files.

Convert target locations to spatial coordinates.

Compute slope angles, intercept for each row of targets, and means.
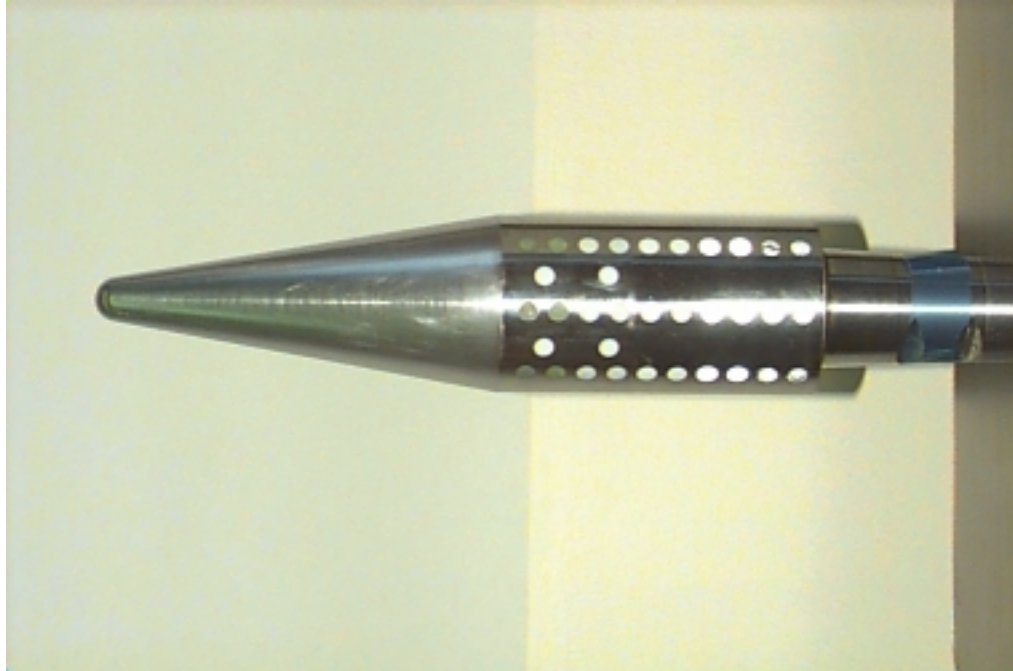
Write data to files.

Figure 2. Calibration cone used to evaluate target schemes at the National Transonic Facility.

Figure 8. VMD model setup showing use of calibration fixture.

Figure 3. PSP Data Acquisition Flowchart

Wind Tunnel

SERVIO

PSP Camera System

Begin taking data.

Send "Take Data" signal to PSP system.

Write tunnel conditions and any conventional force/pressure data to database.

OK to go to next tunnel condition?

No

Yes

Change tunnel conditions.

OK to take next data point?

Is PSP system taking data?

No

Yes

Is wind tunnel finished taking data?

No

Yes

PSP images acquired?

No

Yes

Signal ready to change condition.

Is PSP ready to take new data?

Update image database.

Signal ready to take new data.

Take PSP data?

No

Yes

Signal taking data.

Find best exposure time (if necessary).

Acquire images.

Signal images acquired.

Subtract dark images.

Save image data.
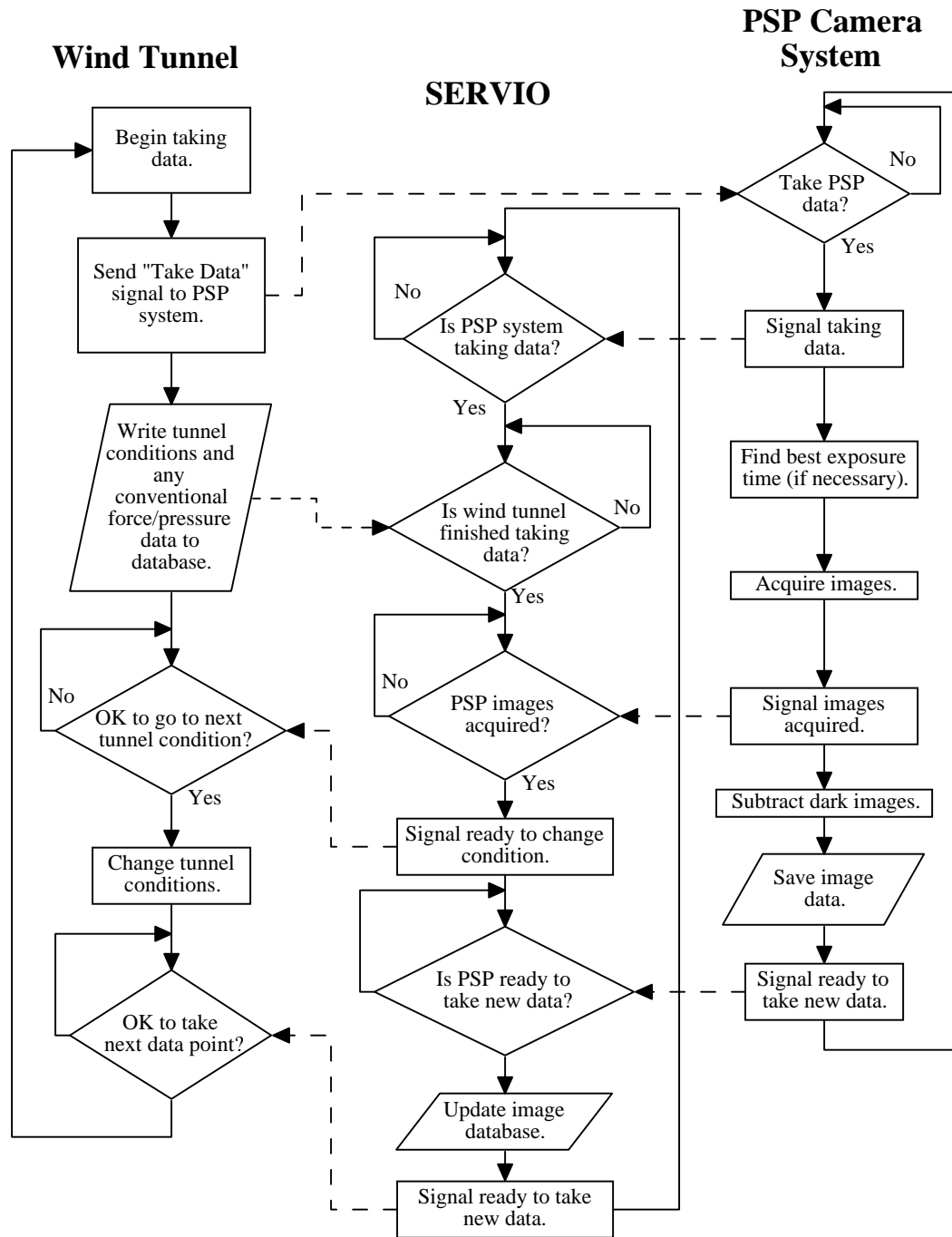
Signal ready to take new data.

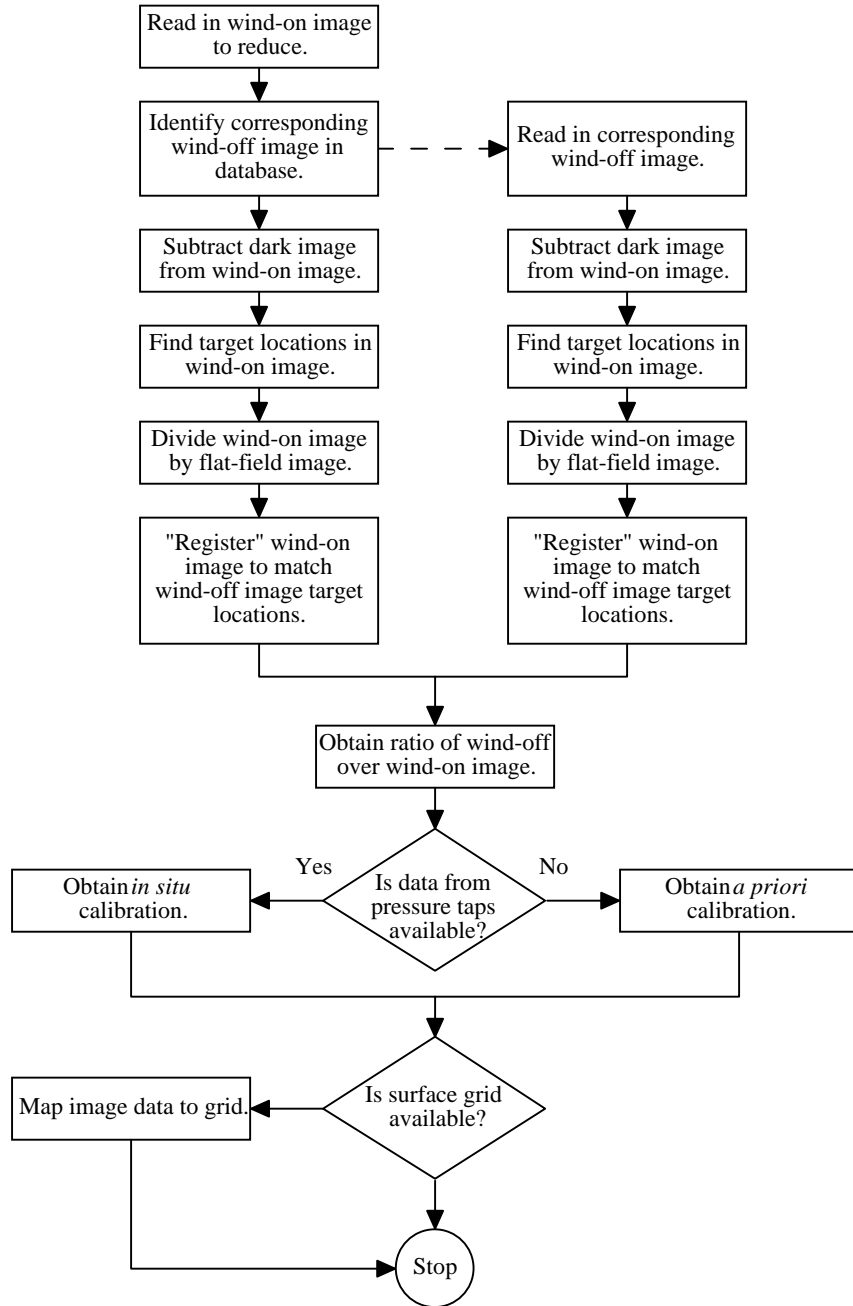**Figure 4. PSP Data Reduction Flowchart**

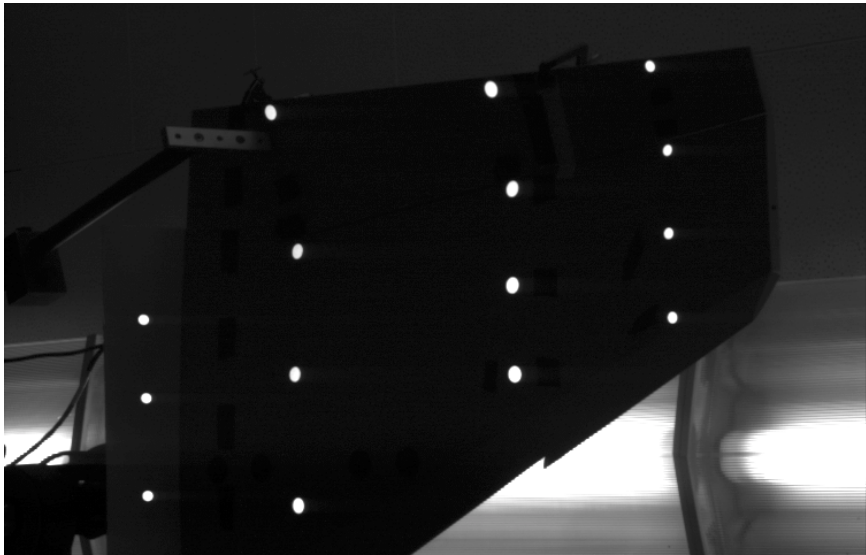Figure 5a. VMD model setup under room lighting.

Figure 5b. VMD model setup with retro-reflective targets illuminated. Note arrangement of targets in rows.

Figure 5c. PSP model under UV illumination. Note evenly spaced targets and targets near edges.
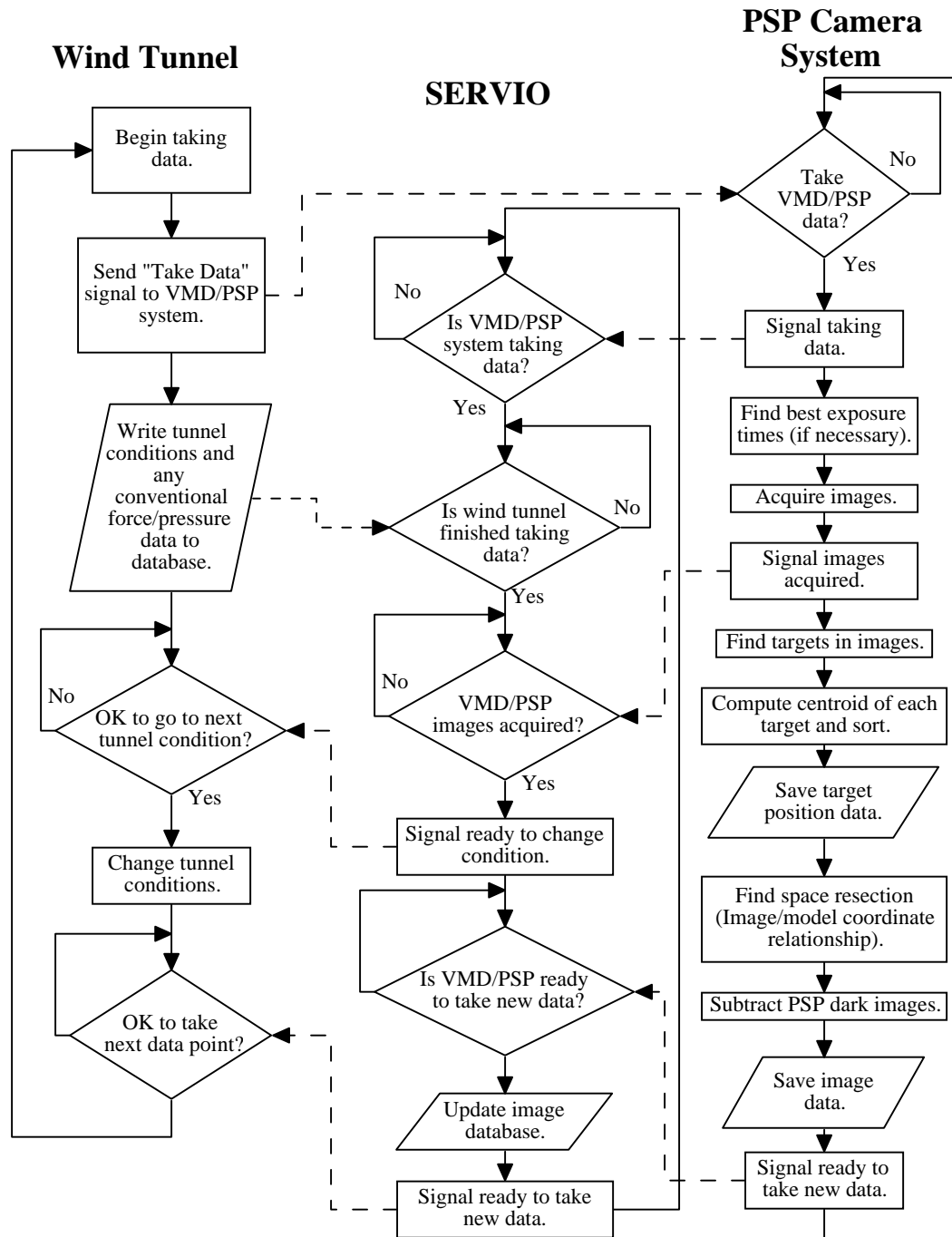
Figure 7. Combined PSP/VMD Data Acquisition Flowchart

Figure 9. Combined VMD/PSP Data Reduction Flowchart

Identify data point to reduce.

Read in wind-on and corresponding wind-off PSP images, target location data, and tunnel condition data from database.

Perform flat-field correction on PSP images.

Determine VMD target positions in model coordinates.

Register wind-off image to wind-on.

Determine model deformation, especially wing bending and twist.

Find ratio of wind-off over wind-on image.

Choose *a priori* or *in situ* calibration?

a priori

in situ

Perform *a priori* calibration.

Perform *in situ* calibration.

Update locations of any model pressure taps.

Map image data to model surface grid.

Update model surface grid point locations.

Store reduced data.