

Technical Notes

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Full-Field Uncertainty Determination for Pressure-Sensitive Paint Measurements

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I. Introduction

THE principle behind pressure-sensitive paint (PSP) measurements is by now well known: a luminescent coating is applied to a test article, the test article is illuminated with light at a short wavelength (for example, blue), and emission from the paint (for example, red) is imaged by one or more digital cameras. Oxygen quenching of the luminescent signal produces the desired pressure sensitivity [1,2].

Pressure distributions are typically computed from the ratio of images based on a suitable calibration equation. In intensity-based measurements, these are images at a wind-off condition and images at the run condition. In lifetime-based measurements, both images are acquired at the run condition by choosing two different temporal gates with respect to a train of excitation pulses. Three-gate measurements are also being developed [3].

Many studies have been performed to assess the error sources in PSP measurements [4–11]. However, assessment of the measurement uncertainty in practice is typically limited to a comparison of PSP data in the vicinity of pressure taps with readings from these taps.

The purpose of this paper is to show that two additional measures of uncertainty can easily be implemented. One is based on pixel-to-pixel variations within an image from a single camera, the other on camera-to-camera variations for points on the test article that are viewed by two or more cameras. In principle, these additional measures of uncertainty can be computed for every point on the surface of the test article. Both produce an estimate of the *precision* of the PSP measurement and may be thought of as adding “error bars” to the processed data in full-field mode.

II. Pixel-Based Uncertainty

The idea behind the definition of a pixel-based uncertainty is that, for most points on the surface of the test article, variations in pressure

take place on a spatial scale that is large compared with the pixel spacing in the acquired images. Thus, pixel-to-pixel variations in the measured pressure are more likely the result of noise in the measurement, specifically, photon shot noise.

Imagine that images have been processed to yield a pressure, P_{ij} , at each pixel (i, j) in the image. In the vicinity of a pixel (i_0, j_0) , the *actual* variation in pressure is assumed to be given by the bilinear form

$$P(i, j) = a + b(i - i_0) + c(j - j_0) \quad (1)$$

The coefficients a , b , and c are obtained by performing a least-squares fit of Eq. (1) to the measured pressures P_{ij} . For each pixel (i_0, j_0) , this calls for solution of the linear system

$$\begin{pmatrix} S_1 & S_i & S_j \\ S_i & S_{ii} & S_{ij} \\ S_j & S_{ij} & S_{jj} \end{pmatrix} \begin{pmatrix} a \\ b \\ c \end{pmatrix} = \begin{pmatrix} S_p \\ S_{ip} \\ S_{jp} \end{pmatrix} \quad (2)$$

Here $S_1 \equiv \Sigma 1$, $S_i \equiv \Sigma(i - i_0)$, $S_j \equiv \Sigma(j - j_0)$, $S_{ii} \equiv \Sigma(i - i_0)^2$, $S_{ij} \equiv \Sigma(i - i_0)(j - j_0)$, $S_{jj} \equiv \Sigma(j - j_0)^2$, $S_p \equiv \Sigma P_{ij}$, $S_{ip} \equiv \Sigma(i - i_0)P_{ij}$, and $S_{jp} \equiv \Sigma(j - j_0)P_{ij}$. These sums extend over a finite region of pixels in the vicinity of the pixel (i_0, j_0) , for example, a 5×5 region of pixels centered on the pixel (i_0, j_0) .

Having computed the solution of Eq. (2), it follows from Eq. (1) that the fitted pressure at the pixel (i_0, j_0) is given by $P(i_0, j_0) = a$. Also, the following quantity, in terms of the solution of Eq. (2), constitutes an unbiased estimator for the variance of the associated measurement noise *per image pixel*:

$$\begin{aligned} \tilde{\sigma}_{\text{pix}}^2(i_0, j_0) &= \frac{1}{N - 3} \sum_{i,j} [P(i, j) - P_{ij}]^2 \\ &= (S_{pp} - aS_p - bS_{ip} - cS_{jp}) / (N - 3) \end{aligned} \quad (3)$$

Here $S_{pp} \equiv \Sigma P_{ij}^2$ and N is the number of pixels in the sum. The factor 3 in Eq. (3) reflects the fact that the fit from Eq. (2) has 3 degrees of freedom.

For most points in the image, Eq. (3) should provide a reasonable estimate of the measurement noise. Points with a strongly nonlinear pressure gradient (for example, points on a shock line) would be an exception, because Eq. (3) would overestimate the measurement error at such points.

III. Camera-Based Uncertainty

When a point on the surface of the test article is viewed by multiple cameras (with index c), we may imagine that multiple values of the pressure, P_{cg} , are measured for the same point g on the surface. (In the following, we will specifically consider the case in which g represents a point on the 3-D grid to which data is being mapped.) We may then define an average pressure, P_g , computed over all camera views for which a value P_{cg} is defined:

$$P_g \equiv \sum_c w_{cg} P_{cg} / \sum_c w_{cg} \quad (4)$$

The weights w_{cg} may be chosen so as to weigh the resulting average preferentially toward points that are viewed most normally by a particular camera, for example, $w_{cg} = (\hat{\mathbf{n}}_c \cdot \hat{\mathbf{n}}_g)^2$, where $\hat{\mathbf{n}}_c$ and

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$\hat{\mathbf{n}}_g$ are unit vectors that correspond to the viewing direction for camera c and the surface normal at point g , respectively.

Averaging camera views as opposed to selecting a single value P_{cg} has the following advantages: all of the camera data is used, the overall noise level of the processed data is reduced, and seams between adjacent camera views are less noticeable in the final data.

Also, an additional measurement uncertainty can be computed by quantifying the degree of disagreement between overlapping camera views. One such measure of disagreement is the quantity

$$\begin{aligned}\chi^2 &\equiv \sum_c w_{cg} [P_{cg} - P_g]^2 / \sum_c w_{cg} \\ &= \left(\sum_c w_{cg} P_{cg}^2 / \sum_c w_{cg} \right) - P_g^2\end{aligned}\quad (5)$$

Here P_{cg} is the mapped pressure for camera c at (grid) point g , P_g is the weighted average from Eq. (4), and w_{cg} is the same weighting factor that is used in the calculation of the weighted pressure value P_g itself.

It can be shown that Eq. (5) can be used to compute a mathematically rigorous rms measurement uncertainty for the camera-weighted pressure P_g from Eq. (4), according to

$$\sigma_{\text{cam},g} = \left[\frac{W}{1-W} \chi^2 \right]^{1/2} \quad (6)$$

where

$$W \equiv \left(\sum_c w_{cg}^2 \right) / \left(\sum_c w_{cg} \right)^2 \quad (7)$$

For example, in the case of two overlapping camera views with measured pressures P_{1g} and P_{2g} and equal weights w_{1g} and w_{2g} , it follows from Eq. (4) that the merged pressure value is given by $P_g = \frac{1}{2}(P_{1g} + P_{2g})$ and it follows from Eqs. (5–7) that the camera-based RMS uncertainty of P_g is given by $\sigma_{\text{cam},g} = \frac{1}{2}|P_{1g} - P_{2g}|$.

IV. Practical Implementation

The calculation of the pixel-based and camera-based pressure measurement uncertainties can be implemented in a variety of ways. The following approach is attractive, given the typical desire to deliver processed PSP data to a test customer in 3-D form:

1) Preprocess image data in the standard manner by performing black subtraction, image registration, patching over registration targets, and normalization by exposure time or by the number of excitation pulses over which the images were integrated [12].

2) Compute image ratios on a per-pixel basis and apply the paint calibration equation to convert image ratios into pixel-based pressure values P_{ij} .

3) For each camera c , map the pixel-based pressures P_{ij} to a 3-D grid by selecting, for each grid point g , the pixel (i_0, j_0) that corresponds to the projection of the grid point g into the image. Then (see Fig. 1) use Eqs. (1) and (2) to compute, for each grid point g , the pressure P_{cg} that is obtained by fitting the pixel-based pressures P_{ij} in a region of pixels surrounding the pixel (i_0, j_0) , yielding $P_{cg} = a$ in terms of Eq. (2). Depth-buffer masking may be used in this process to prevent the usage of image pixels that are not located in the vicinity of the grid point g in 3-D space. Also, compute the associated pixel-based variances σ_{pix}^2 from Eq. (3).

4) For each grid point g , merge overlapping camera views c using Eqs. (4–7) to produce a camera-weighted pressure, P_g ; a pixel-based RMS uncertainty, $\sigma_{\text{pix},g}$; and a camera-based RMS uncertainty, $\sigma_{\text{cam},g}$. Composite uncertainties (averaged over the entire grid) may also be computed.

This approach (in essence) was implemented as part of the PSP data reduction scheme that is used at the Arnold Engineering Development Center (AEDC) [12].

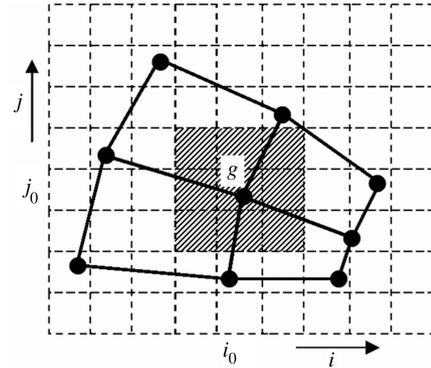


Fig. 1 Mapping image pixels to a projected 3-D grid.

V. Illustration of Concept

To illustrate the concept of full-field uncertainty determination for PSP measurements, Figs. 2–4 show results that were obtained in a lifetime-based PSP test of a scale model of the NASA space shuttle in October 2004. (Only qualitative results were released for publication; the actual data are quantitative in nature.) These measurements were performed in AEDC's 16-ft transonic wind tunnel, using eight cameras in the test section. This means that most points on the surface of the test article were imaged by two, three, or four cameras. Further details may be found in Ruyten and Sellers [13] and Bell and Sellers [14].

Areas of high and low measurement uncertainty in Figs. 3 and 4 correlate strongly with areas of high and low pressure, respectively, in Fig. 2. This is the expected behavior when photon shot noise is the dominant source of error. Elevated uncertainties are also observed in areas that were mostly shielded from the excitation lights due to the complex geometry of the test article.

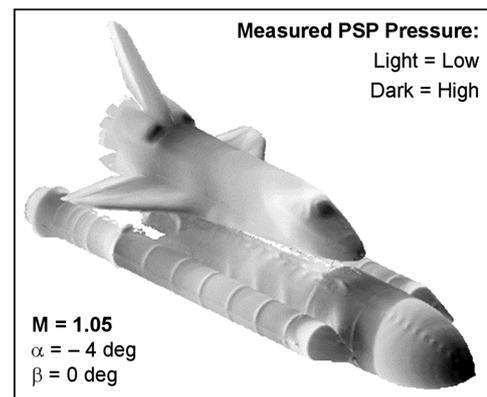


Fig. 2 Measured PSP pressure distribution on space shuttle model.

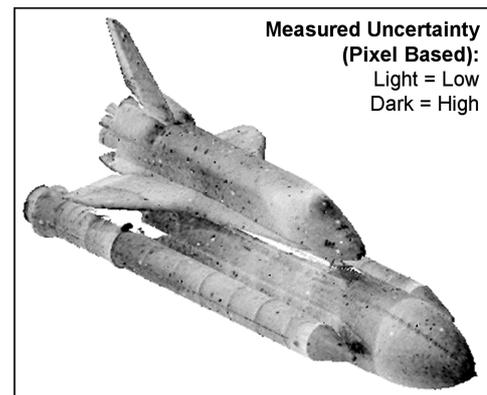


Fig. 3 Pixel-based RMS measurement uncertainty for data from Fig. 2.

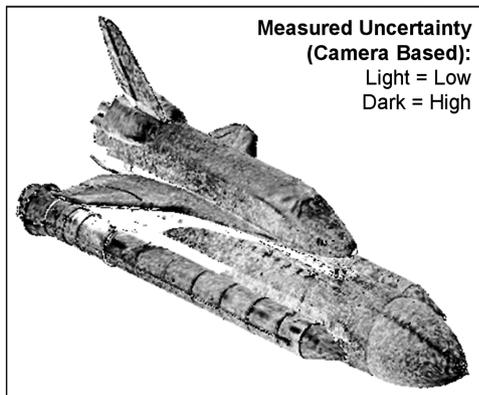


Fig. 4 Camera-based RMS measurement uncertainty for data from Fig. 2.

VI. Conclusions

It has long been customary to quote measurement uncertainties for PSP data that are presented as line cuts along rows of pressure taps. However, a similar presentation of measurement uncertainties for full-field PSP data has not been reported previously. Here it is shown that such can be accomplished by suitable processing of the data. In particular, it has been shown that pixel-based uncertainties can be reported for all points on the test article for which PSP pressures are being computed, and that camera-based uncertainties can be reported for all points that are viewed by two or more cameras.

This is not to say that the new diagnostic quantities can replace the need for pressure taps altogether. In particular, the pixel-based and camera-based measurement uncertainties are *not* sensitive to certain systematic effects, such as the uncompensated temperature dependence of the paint or other problems associated with the conversion of image ratios to pressure. In this regard, the pixel-based and camera-based uncertainties place a *lower* limit on the achieved *accuracy* of the PSP measurement.

Nevertheless, the methodology for computing pixel-based and grid-point-based pressure measurement uncertainties should provide a useful addition to the standard approach for processing and presenting PSP data from a ground test facility.

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