

Reference-Free, Projection Background-Oriented Schlieren

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A projection background-oriented schlieren (P-BOS) system is developed and demonstrated. Instead of a background that has a speckle pattern printed, painted, or otherwise deposited onto its surface, and can thus not be altered, the pattern here is projected onto the background. This allows for changes to the speckle pattern without replacement of the background material, which can be time-consuming and expensive. Reference images are acquired simultaneously with flow images. A pre-test transformation between the reference and flow images allows for on-the-fly changes to the speckle pattern during a test without requiring a stoppage of the flow, allowing for optimization of the BOS signal. Using a programmable LCD screen as the speckled optic allows for remote control of the speckle pattern. Because the background is not speckled, the system can be easily transformed to acquire shadowgraph images by removing the speckled optic and closing the aperture of the light source, which is useful for achieving measurements with higher spatial resolution. The system can be nearly as compact as a conventional BOS system, and can be assembled with polarized optics to reduce or eliminate window reflections and glare, making this system particularly well-suited for wind tunnel testing.

I. Introduction

Using conventional schlieren and shadowgraph as non-intrusive methods of visualizing fluid flow fields has been a powerful tool of researchers for decades [1, 2]. High quality mirrors or lenses are needed, which can become prohibitively expensive for larger fields-of-view, and it requires optical through-access across a wind tunnel, for example, which may not be available for every facility. Background-oriented schlieren (BOS) is similar to conventional schlieren methods in that it is sensitive to index of refraction/density gradients [3–9]. Further comprehensive information about the technique can be found in Refs. [2, 10]. For BOS, a camera views a speckled background pattern on the opposite side of the density object of interest, and displacements/shifts in the background pattern due to the density gradients can be computed. Benefits of using BOS over conventional schlieren include: expensive mirrors/lenses are not required, optical through-access is not required, the field-of-view is only limited by the camera/lens and background size, and it is generally less time-consuming to set up.

There are several variants of the BOS technique currently in use. Using natural backgrounds such as vegetation allows for large field-of-view measurements [11, 12], including helicopter rotor vortex [13–17] and aircraft shockwave imaging [18, 19]. A similar method, this time viewing up at celestial objects (e.g., the sun) is called BOS using Celestial Objects, or BOSCO [20, 21]. This method uses either a Calcium-K filter (CaKEBOS) or a Hydrogen-alpha filter. Retroreflective BOS (RBOS) uses a retroreflective material for the background, increasing light intensity return and allowing for shorter camera exposure times [22, 23]. Using laser-speckle as the illumination source with RBOS provides a highly structured background pattern using the light source itself [24–27]. A non-retroreflective laser speckle system has also been recently reported on, but requires line-of-sight access across the flow of interest [28]. Real-time BOS has also been recently demonstrated by using a self-illuminated background screen that can be adjusted on-the-fly to use the optimal background pattern, with real-time calculation of displacements, limited only by the processing power of the computer [29, 30]. A reference-free digital shadowgraphy measurement uses a shifting background to avoid needing a reference image, and measures the second derivative of density [31].

For retroreflective BOS, commonly used in ground test facilities, the speckle pattern is sprayed/printed directly onto the retroreflective (or *retro*) material prior to testing. The size and density of the speckle pattern must be calculated ahead of time to achieve optimal results, and once it is applied, it cannot be changed. The exact pattern can be printed onto the retro backgrounds, as facilitated by Heineck for the work in Ref. [32], but if spray painting the pattern, the size and density is not easily controlled. High-quality, high-intensity-return retro material is expensive, and if the pattern must be changed, an entirely new sheet of the retro material must be used. Laser speckle RBOS does not require the

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spraying/printing of a speckle pattern on the retro material, since it is projected onto the material by the laser beam, and the constructive/destructive interference of the laser with the retro provides the pattern [25]. While this avoids the need to re-speckle retro material, changing the laser speckle size requires a change in the $f/\#$ of the projecting lens [24]. While the speckle size can indeed be changed, the range of speckle size/density remains limited (see Fig. 7 in [24]). Additionally, the system becomes sensitive to vibrations (see Section V of Ref. [25]).

The projection BOS (P-BOS) system described in this paper is able to overcome some of the limitations mentioned previously. The system projects a speckle pattern onto an un-speckled piece of retro material on the opposite side of the density object of interest, using either a physical patterned optic (transparent glass/plastic slide with a pattern printed onto its surface) or a digital LCD screen. Both a reference image of the projected pattern and a density-gradient-distorted flow image are simultaneously acquired, and using a pre-test transformation between the two images, the speckle pattern can be changed during a run to allow for BOS signal optimization. The lack of speckling of the background also allows for shadowgraph images to be acquired with minor changes to the system, and using polarization optics in the system minimizes reflections/glare from windows. A polarized implementation of the P-BOS system is described in Section II.A, and its transformation to a shadowgraph system discussed in Section II.B. The process of computing the transformation required for reference-free operation is detailed in Section III.A. The thermal plume of a heat gun is used to demonstrate the system's capabilities while using a physical patterned optic in Section III.B, and when using a digital LCD display in Section III.C. The shadowgraph implementation of the system is then demonstrated in Section III.D, and finally, the system is installed at the 20-Inch Mach 6 wind tunnel facility to make measurements on a flat plate model in Section III.E.

II. Experimental Setup

A. Projection-BOS System

The polarized implementation of the P-BOS system is shown schematically in Fig. 1, where colored lines represent the polarization state of the light as it travels through the system. Red denotes linearly-vertically polarized light (lvp), magenta is right-circularly polarized light (rcp), cyan is left-circularly polarized light (lcp), and blue is linearly-horizontally polarized light (lhp). Light from a light source (LS) is loosely collimated and diffused using a short focal length condenser-diffuser lens (CD). This light then passes through a patterned optic (PO), which here is a transparent soda lime glass substrate with an opaque chrome pattern deposited on its surface. The light (which can have any polarization state, or be unpolarized) passes through an optional linear polarizer (LP) or half-wave plate (HWP) to condition the polarization state prior to passage through a polarizing beamsplitter (PBS). The PBS allows a portion of the light to pass through it, which exits as lhp light, passing through another linear polarizer (LP^{Ref}), and is imaged by a camera (Ref) with a lens (L^{Ref}). The PBS also reflects a portion of the light onto the main optical axis of the system, which exits as lvp light, passing through a field lens (FL) which images the PO onto a retroreflective background (RBG) on the other side of the density object of interest (DO). Depending on the testing location, a window (W) may be present on either or both sides of the DO. The polarized system is ideally suited to reduce window reflections when operating at normal incidence to a window. The outgoing lvp light will reflect at the window surface, but remain lvp , which is reflected out of the system by the PBS. The light that transmits through the DO passes through a quarter-wave film (QWF) placed in front of the RBG, which when oriented appropriately, transforms the lvp light to rcp light. Retroreflection at the RBG flips the handedness of this polarization from rcp to lcp , which upon passage through the QWP is converted to lhp . This lhp light is then allowed to transmit through the PBS, another linear polarizer (LP^{Sig}), and into a camera (Sig) through a lens (L^{Sig}).

Any light source can be used for this system, and results using both an unpolarized LED and a polarized laser are presented in subsequent sections. When using the polarized P-BOS system as shown in Fig. 1, polarization of the incoming light to the PBS can be used to more efficiently split light between the Ref and Sig cameras. If using an unpolarized light source, the LP is used to transmit only a linear polarization state of the light through the PBS. Regardless of the orientation of the LP, it will reduce the intensity by half. If the LP is oriented to pass only lvp light, then all the light will be reflected by the PBS, and no light will be transmitted through to the Ref camera. Conversely, if the LP is oriented to pass only lhp light, all the light will be transmitted to the Ref camera, and none will be reflected onto the main optical axis. The LP can be rotated to some intermediate angle such that sufficient signal is available for both the Ref and Sig cameras. In practice, the LP is oriented to reflect more light at the PBS because some of this light

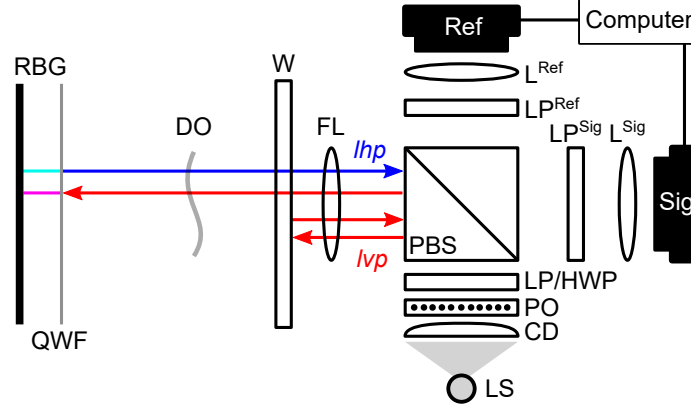


Fig. 1 Polarized P-BOS system schematic, with colored lines representing various polarization states of light: red-*lvp*, blue-*lhp*, magenta-*rcp*, cyan-*lcp*.

is lost through transmission of the extra optics/windows, and upon reflection at the RGB. If using a polarized light source such as a laser, the light is typically highly-linearly polarized already. A HWP is used instead of the LP, such that the linear polarization state can be rotated relative to the PBS. The same intensity splitting is achieved, but unlike the LP, none of the LS intensity is lost through the HWP.

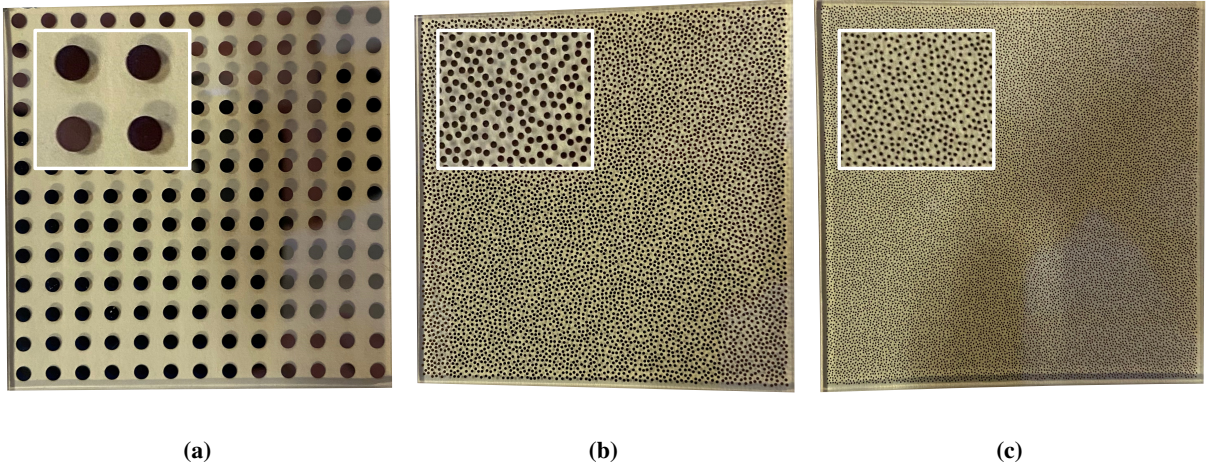


Fig. 2 Images of the physical POs, including the (a) regular dot pattern calibration optic, the (b) 0.4 mm dot size/spacing optic, and the (c) 0.2 mm dot size/spacing optic. Insets show a zoomed view of the pattern.

Images of three POs are shown in Fig. 2, with insets at the top-left of each image showing a zoomed view of a small portion of the optic. Each PO is a 1.52-mm-thick, 52-mm-square soda lime glass substrate with a low-reflective opaque chrome pattern deposited on its surface. They are all coated on both sides with a BBAR anti-reflection coating centered at 640 nm, as this is the wavelength of light typically used for both the LED and laser imaging. In Fig. 2a, a regular dot pattern optic is shown, comprising a regular grid of 13×13 circles of 2-mm-diameter, with their centers separated by 4 mm in both horizontal and vertical directions. Figures 2b and 2c show images of POs with random dot patterns of 0.2 mm and 0.4 mm dot size/spacing, respectively. These patterns were generated using the LaVision™ Random Pattern Generator software. These POs can be easily swapped in and out of the system using a custom 3D printed mount with a set-screw to hold it in place.

The physical PO can be replaced with a digital display (LCD/TFT screen) to allow for on-the-fly updates to the speckle pattern. This can be a useful option when fine adjustments of the pattern are required, or when multiple patterned optics cannot be purchased (e.g., due to cost limitations). One option for the LCD inclusion is to remove the LS and CD, and place the screen in the place of the PO. In this implementation, the LCD screen is back-lit with its own

internal light. The second option is to simply replace the PO with a transparent LCD screen, allowing for the LS to provide the illumination. Results from both implementations are presented in Section III.C.

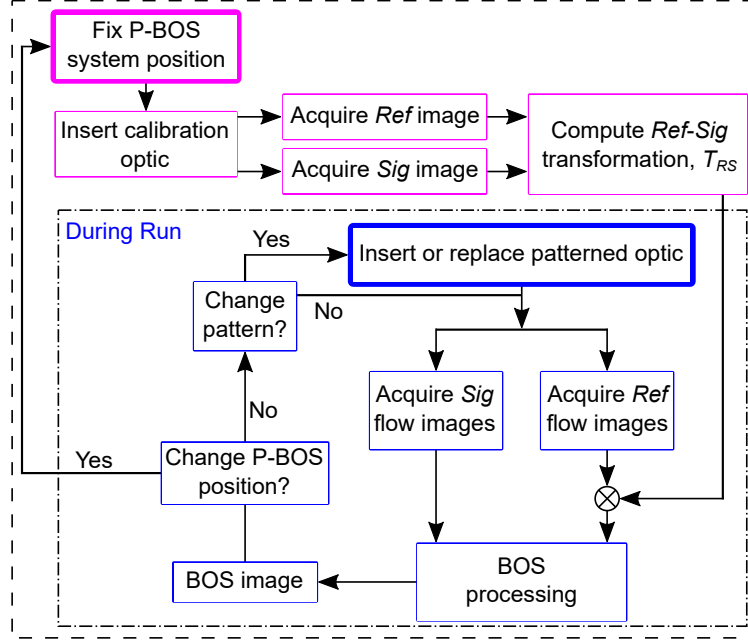


Fig. 3 Flowchart for the setup, calibration, and running of the P-BOS system.

A flowchart for operation of the P-BOS system is shown in Fig. 3. Tasks that must be completed prior to a test are outlined in magenta, while tasks completed during a test are outlined in blue (and enclosed with a dash-dot line). The starting point for magenta tasks and blue tasks are denoted with bold outlines. If the P-BOS system positioning and alignment does not change after the initial calibration, then the magenta procedure need only be performed once. If the positioning of the system does change, then the magenta procedure will need to be performed again for each position change (including changes in focal length, aperture, focus, etc.).

Starting with the bold magenta box in Fig. 3, the positioning of the P-BOS system and its optics are fixed in place. This is done in a similar manner to a conventional BOS system, although here the FL must be adjusted such that the PO is projected sharply on the RBG prior to adjustment of the *Sig* camera, because the *Sig* camera images through the FL. The optic used for the calibration is placed in the PO position (see Section III.A), and two images are acquired, one with the *Ref* camera and one with the *Sig* camera. A transformation is computed, T_{RS} , which warps the *Ref* image coordinate system to that of the *Sig* image coordinate system, effectively accounting for all the optics present in the system. As long as the P-BOS system remains fixed, this transformation from *Ref*-to-*Sig* will remain valid, and the PO can be continuously changed during a run without stopping the flow, either by swapping out a physical patterned optic, or by changing the digital speckle pattern projected from an LCD screen. The desired speckled optic is now inserted into the PO position (bold blue box). Note that if using the speckle pattern optic for the transformation calculation, the PO does not need to be replaced. The density object is introduced (i.e., the flow is turned on), and simultaneous *Ref* and *Sig* images are acquired. For each image pair, the *Ref* image coordinate system is transformed to the *Sig* image coordinate system using the previously computed T_{RS} . The two images are then fed into the BOS processing code, which in a simple implementation is a cross-correlation algorithm, and the result is a pixel displacement BOS image for that time step's image pair. Should a different dot size/spacing/density be required, perhaps for BOS signal optimization purposes, the PO can be replaced or changed during the test while the density object is still present, and the BOS processing repeated using the same transformation.

B. Shadowgraph System

There are two distinct benefits of not speckling the retroreflective material directly. The first is that the RBG can be used for other simultaneous imaging purposes, as demonstrated in Section III.E when the P-BOS system is used to make

simultaneous measurements with a focusing schlieren system. The second is that the P-BOS system can be converted for use as a shadowgraph system, shown schematically in Fig. 4. The schematic shows a shadowgraph system converted from a non-polarized version of the P-BOS system, but the same can be done with the polarized system.

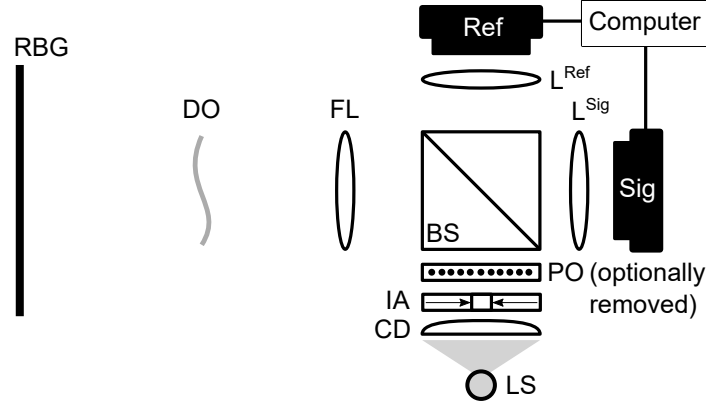


Fig. 4 Schematic of shadowgraph implementation using a non-polarizing P-BOS system. The same changes are needed when using the polarized system of Fig. 1.

Here, an adjustable iris aperture (IA) is closed down to make the light from the LS an approximate point source. If a physical PO is used, it is removed from the system, while if an LCD screen is being used, the pattern can be removed such that the screen fully transmits light. The *Ref* camera is not needed for shadowgraph imaging, so if a polarizing system is being used, all the light can be reflected onto the main optical axis, since it is likely that the *Sig* camera will need to have an increased exposure due to the IA blocking some of the light from the LS.

III. Results and Discussion

A. Reference/Signal Transformation

Once the P-BOS system has been set up in its position for testing, a calibration between the *Ref* camera and *Sig* camera is performed. This need only be computed once prior to testing, as long as the system is not moved to a different location, and the optics remain fixed. If the speckle slide/pattern is changed without changing the system position/optics, this calibration remains valid. A regular two-dimensional grid of circular dots is used for the calibration slide as shown in Fig. 5a. As mentioned previously, the clear glass slide is 52-mm-square, with a regular grid of 13×13 opaque, low-reflective chrome circles of 2-mm-diameter, with center-to-center separation of 4 mm in both directions. The 1.52-mm-thick soda lime glass slide has a double-sided BBAR anti-reflection coating centered at 640 nm.

Images of the regular dot pattern optic taken with the *Ref* and *Sig* cameras are shown in Fig. 5b and Fig. 5c, respectively. The black circular outline denotes the edge of the field-of-view, limited by the 50 mm aperture of the optics used in this particular system. The number of dots visible in both camera images shows that there is very little difference in magnification between the two images; this results in a transformation that does not distort the *Ref* image much. Insets in both images show a zoomed view of the dots, where the dots in the *Ref* image of Fig. 5b appear sharp and the dots in the *Sig* image of Fig. 5c appear slightly softer at the edges. This is because the *Ref* camera is directly imaging the PO (through the PBS), while the *Sig* camera is imaging the pattern after it has been reflected at the PBS, projected by the FL, retroreflected by the RBG, and then re-imaged by the FL onto the *Sig* camera. It is most likely the retroreflection at the RBG that has the largest impact on the softening of the edges.

A two-dimensional polynomial transformation is used in this work, and has been demonstrated to provide a good transformation for all cases tested thus far. The transformation from *Ref* image coordinates to *Sig* image coordinates can be computed (T_{RS}), or the transformation from *Sig* image coordinates to *Ref* image coordinates can be computed (T_{SR}). For the discussion here, the *Source* image (src) is being transformed to the *Target* (tgt) image's coordinate system. First, the x and y pixel locations of the centers of the dots are identified for both images, and are stored in the variables X_{src} ,

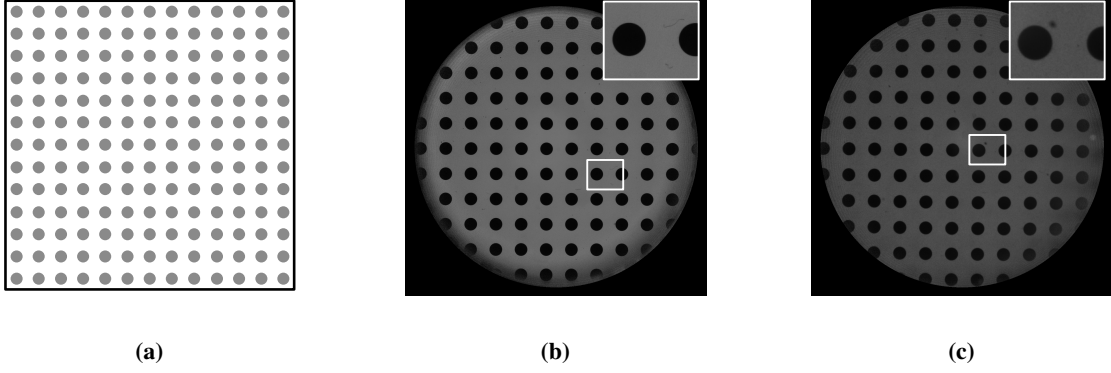


Fig. 5 Regular dot pattern optic (a) schematic, imaged by the (b) *Ref* camera and the (c) *Sig* camera, with 2-mm-diameter circles with a center-to-center separation of 4 mm, and insets showing a zoomed view of the dots.

Y_{src} , X_{tgt} , and Y_{tgt} . Using the *Source* image dot locations, the matrix A_{src} is constructed in Eq. 1, which is a matrix of size $[N \times 10]$, where N is the number of dot pairs identified in the images.

$$A_{src} = [1, X_{src}, Y_{src}, \dots, X_{src}X_{src}, X_{src}Y_{src}, Y_{src}Y_{src}, \dots, X_{src}X_{src}X_{src}, Y_{src}Y_{src}Y_{src}, X_{src}X_{src}Y_{src}, Y_{src}Y_{src}X_{src}]^T \quad (1)$$

The goal is to find the transformation arrays, T_x and T_y , that map the coordinate system of the *Source* image to that of the *Target* image, using Eq. (2).

$$\begin{aligned} X_{tgt} &= A_{src} T_x \\ Y_{tgt} &= A_{src} T_y \end{aligned} \quad (2)$$

The transformed *Source* image pixel locations, $I_{x,T}$ and $I_{y,T}$, are calculated using these coefficients at every pixel position of the full resolution *Target* image using Eq. (3) and Eq. (4).

$$\begin{aligned} I_{x,T} &= T_x(1) + T_x(2)I_x + T_x(3)I_y + T_x(4)I_xI_x + T_x(5)I_xI_y + T_x(6)I_yI_y + \dots \\ &\quad T_x(7)I_xI_xI_x + T_x(8)I_yI_yI_y + T_x(9)I_xI_xI_y + T_x(10)I_yI_yI_x \end{aligned} \quad (3)$$

$$\begin{aligned} I_{y,T} &= T_y(1) + T_y(2)I_x + T_y(3)I_y + T_y(4)I_xI_x + T_y(5)I_xI_y + T_y(6)I_yI_y + \dots \\ &\quad T_y(7)I_xI_xI_x + T_y(8)I_yI_yI_y + T_y(9)I_xI_xI_y + T_y(10)I_yI_yI_x \end{aligned} \quad (4)$$

The original *Source* image is then interpolated to the new image coordinate system defined by $I_{x,T}$ and $I_{y,T}$. The amount of anchor points used for the transformation is limited by the number of dots on the calibration slide as imaged by both cameras.

The limitations of the regular dot pattern PO for transformation calculations were outlined previously. The first is that the PO must be replaced with the speckled PO prior to testing, and the second is that the number of anchor points used for the calculations is limited by the number of dots. Both of these limitations can be avoided by simply using the speckled PO for the transformation calculations. By using windowed cross-correlations to determine pixel shifts (akin to the dot shifts of the regular dot pattern PO), the resolution of the anchor points can be changed. For example, the images of Fig. 6 show the steps of the transformation calculation for two window sizes. The image is broken into a 10×10 grid as shown in the top-left (TL) quadrant of Fig. 6a, and into a 20×20 grid as shown in the TL quadrant of Fig. 6b. Note that for demonstration purposes, the *Source* and *Target* images for Fig. 6a are the *Sig* and *Ref* images, respectively, while for Fig. 6b, they are the *Ref* and *Sig* images, respectively. For each window, the displacement vector from the *Source* to the *Target* image is computed, with the resulting vectors shown in the top-right (TR) quadrants of Figs. 6a,b. The direction of the vectors shows that the *Sig* image is more magnified than the *Ref* image. Note that the scale of these vectors is increased for clarity, and the true displacement is smaller. This can be more clearly seen in the bottom-left (BL) quadrants of Figs. 6a,b, which show a difference image of the pre-transformation *Source* and *Target* images. The dark and light speckling indicates that the two images are not aligned. The post-transformation

difference images are shown in the bottom-right (BR) quadrants of Figs. 6a,b, with a flatter gray color over the entire image, indicating a successful transformation.

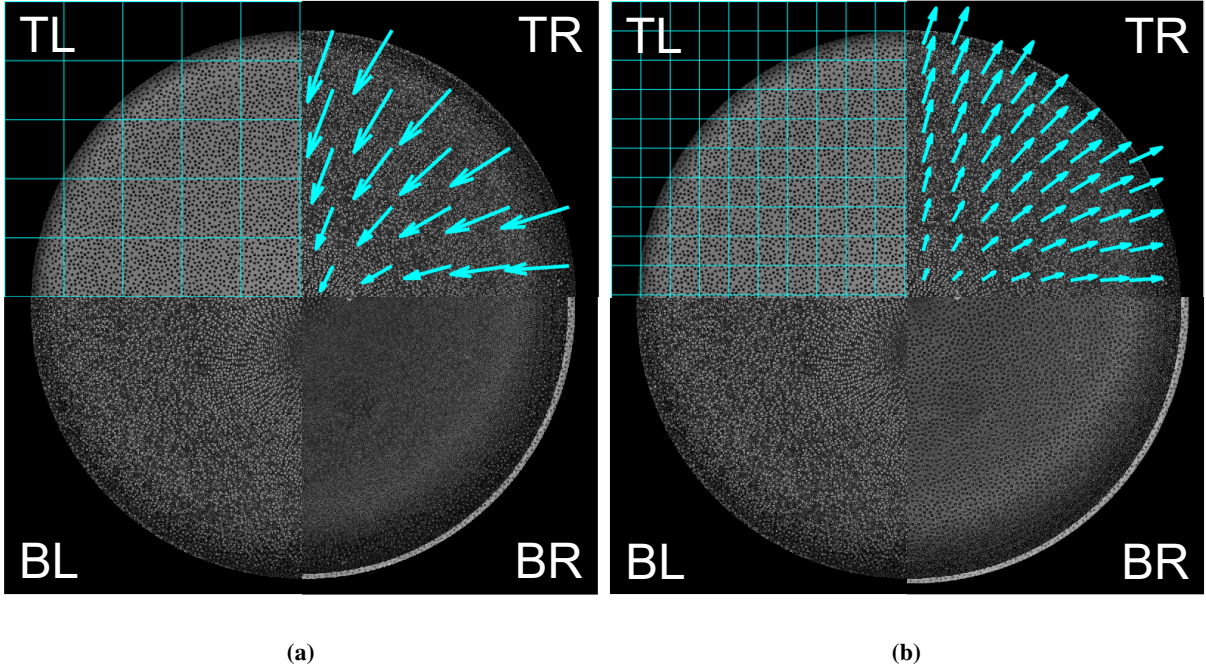


Fig. 6 Transformation calculation using cross-correlation for the 0.2 mm PO, using (a) 10×10 windows and (b) 20×20 windows. The *Source* and *Target* images are (a) *Sig* and *Ref*, and (b) *Ref* and *Sig*, respectively. Quadrants represent (TL) window grids in cyan, (BL) pre-transformation *Source* and *Target* difference image, (TR) cross-correlation result displacement vector, and (BR) post-transformation difference image.

Some final remarks about the transformation process are warranted. As mentioned earlier, when using the regular pattern PO for the transformation, it will need to be replaced with the speckled PO prior to the test. The use of the speckled PO for the transformation means this replacement step is not required, although changing of the speckle pattern itself will require a physical change of the optic. If using an LCD for the PO, the pattern can be simply changed by displaying a new image on the LCD screen, and no physical change is needed. The cross-correlation of the 0.2 mm PO works well. However, if using a finer pattern with a substantial mismatch between the *Ref* and *Sig* images, it is possible the cross-correlation will pick up spurious correlations. It may be beneficial to use a bulk image translation first if the mismatch is large, in order to align the images more closely. As long as the two steps (translation, cross-correlation) are stored in the full transformation, T_{RS} , then this can be applied without issue during the calculations. The regular pattern optic used for the initial transformation demonstration worked well because the images were very nearly aligned prior to the transformation. However, if there is a larger misalignment/shift between the two, the dot correspondence may be incorrect prior to the calculation. That is, if the *Ref* image shows dots that are actually shifted by approximately one row to the left of the *Sig* image, then the automatic dot correspondence calculation will assume that the nearest neighboring dots are to be used for the transformation, when in reality, it should be a much larger transformation. This can be solved by using a regular dot pattern PO with anchor points of different shape, as is customary for typical calibration targets, which use different shapes for the origin definition (triangles, squares, open circles, etc.). Finally, another option for the transformation calculation that has been used successfully is the ImageJ plugin, *bUnwarpJ*. Note, however, that some iterative refinement of the settings of the plugin might be required to get a successful transformation.

B. Physical Patterned Optic P-BOS Imaging

Two physical POs were used to test the P-BOS design, as described in Section II.A and shown in the images of Fig. 2b (0.4 mm dot size/spacing) and Fig. 2c (0.2 mm dot size/spacing). For initial testing of the system, a canned air jet was used to provide a density object, with two resulting P-BOS images shown in Fig. 7a and Fig. 7b for the

0.4 mm and 0.2 mm speckle sizes, respectively. BOS displacement images in this section are computed using the LaVision™ Davis 10 2D BOS processing software. A low-power LED unit was used in continuous mode for these images, so the exposure of the camera required for each image was relatively long compared to the turbulent structure evolution of the jet, resulting in a smoothed jet profile in both images. However, the plume is clear in both images, and is more highly resolved when using a finer speckle pattern (Fig. 7b). In the full image sequences of the jet for both POs, the background room air currents are also visible, providing an indication of the sensitivity of the system.

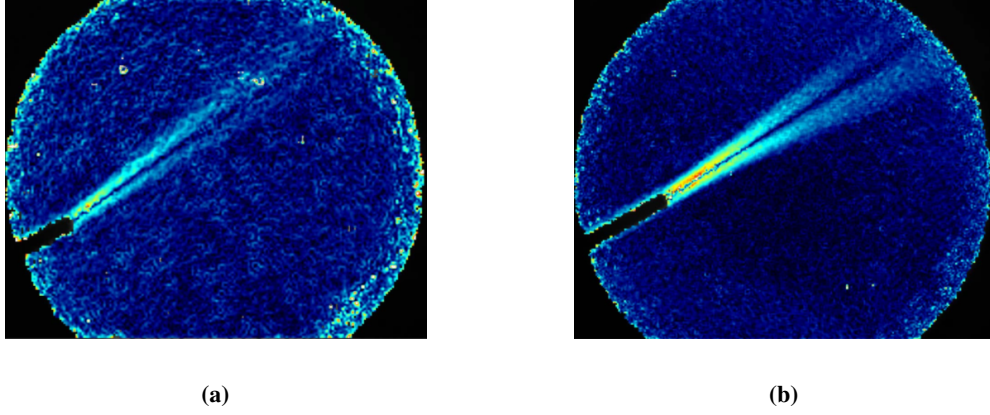


Fig. 7 Canned air jet BOS results using a PO with (a) 0.4 mm dot size/spacing and (b) 0.2 mm dot size/spacing.

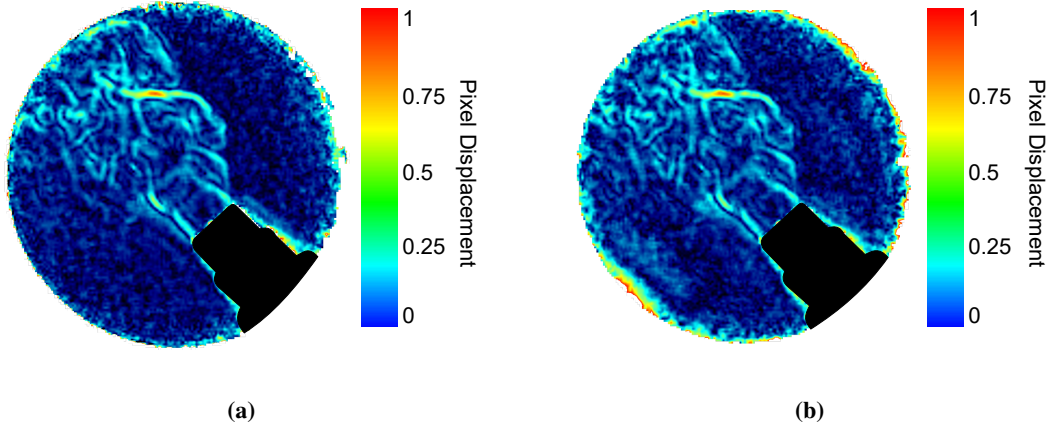


Fig. 8 Heat gun BOS results using a speckle dot size of 0.2 mm and background-divided images for (a) *Sig* comparison to no-flow *Sig* image, and (b) *Sig* comparison to transformed *Ref* image.

The BOS images of Fig. 7 were computed using only the *Sig* camera images, with a flow-off *Sig* image being used as the reference image for the flow-on *Sig* image. In the images of Fig. 8, the validity of using the *Ref* camera image as the reference image for the *Sig* camera image is explored. Here, the thermal plume from a heat gun is used as a stronger, physically-larger density object for easier visual comparison, using the 0.2 mm PO for all images. First, a flow-on *Sig* image BOS signal was computed using a flow-off *Sig* image as the reference, with resulting BOS image shown in Fig. 8a. Then, a T_{RS} transformed *Ref* camera image was used as the reference for the same *Sig* flow-on image, with resulting BOS image shown in Fig. 8b. Both images show a substantially similar result of the thermal plume, but differ near the edges of the circular measurement region. In Fig. 8a, there is low noise at the edge of the image, whereas in Fig. 8b, higher pixel displacements indicate a mismatch between the *Ref* and *Sig* images. This is likely due to the lower signal-to-noise in the images near edges, resulting in reduced accuracy of the T_{RS} calculation near the edges. Since this deviation in signal only occurs at the boundaries of the image, it can be accounted for during system setup, where the boundaries of the field-of-view can be made larger than the flowfield of interest, and can be masked out in the final images.

In Fig. 8, the validity of using the *Ref* image as the reference image for the flow-on *Sig* image was demonstrated,

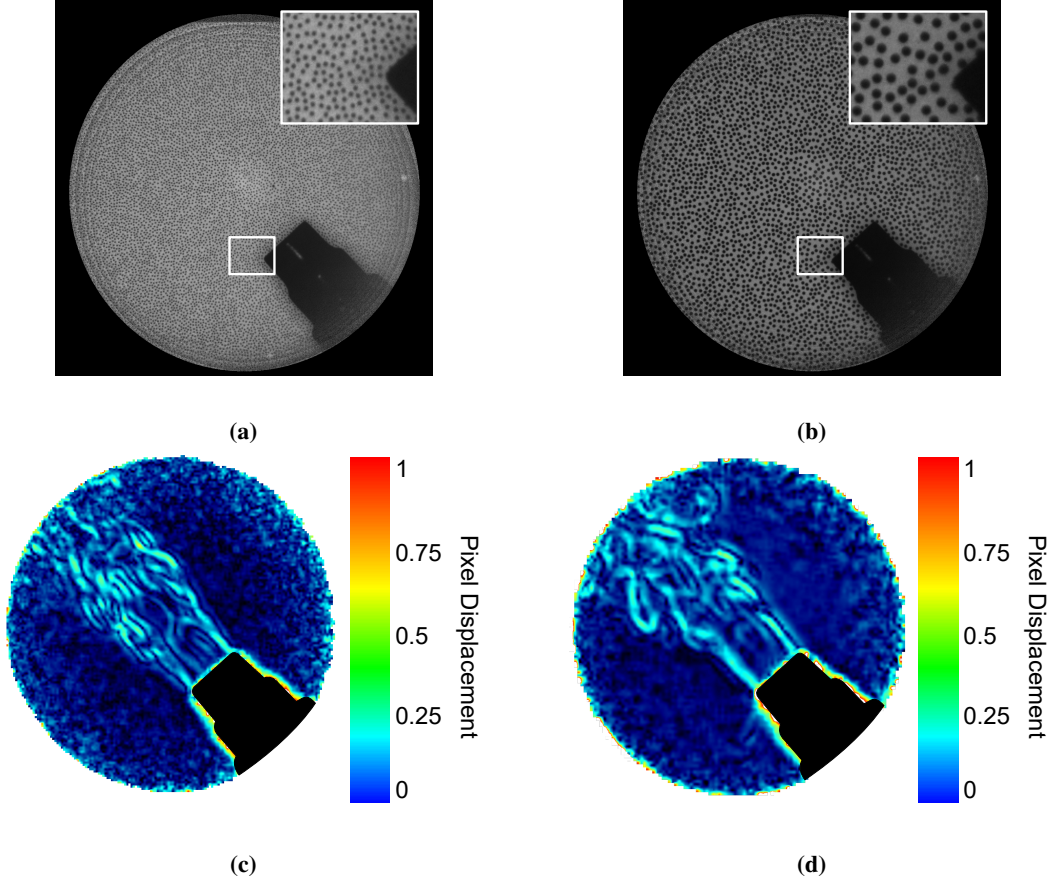


Fig. 9 Background-divided *Sig* images of a heat gun using the (a) 0.2 mm and (b) 0.4 mm PO. BOS pixel displacement results for (c) the 0.2 mm PO and (d) the 0.4 mm PO, where both *Ref* images used in the calculations are transformed using the 0.2-mm-computed transformation, $T_{RS}^{0.2}$.

using the same PO for both (0.2 mm). Here, the ability to change the PO to a substantially different speckle pattern and compute the resulting BOS signal without the need for another flow-off image is explored. Figure 9a shows a background-divided *Sig* image of the heat gun using the 0.2 mm PO, with the inset showing detail of the heat gun nozzle and speckle pattern. The T_{RS} transformation using the 0.2 mm is computed, $T_{RS}^{0.2}$. The resulting pixel displacement BOS signal of the image in Fig. 9a using the $T_{RS}^{0.2}$ -transformed *Ref* image is shown in Fig. 9c, with the heat gun thermal plume visible. This is the same processing sequence used for the results of Fig. 8b. Now, the 0.2 mm PO is replaced with the 0.4 mm PO without stopping the heat gun. The background-divided *Sig* image is shown in Fig. 9b, again with the inset showing detail of the heat gun nozzle and larger speckle pattern. A transformation between the *Ref* and *Sig* images cannot be computed now, because the heat gun remains on, constantly distorting the *Sig* image pattern. Instead, $T_{RS}^{0.2}$ is used to transform the 0.4 mm *Ref* image, which is then used as the reference image in the BOS calculation, a result of which is shown in Fig. 9d. The thermal plume appears qualitatively similar to that of Fig. 9c, albeit with slightly more smeared out structures due to the doubling in size/spacing of the speckle pattern. This demonstrates the ability of the system to operate as a quasi-reference-free projection BOS system, as long as one transformation is computed between the *Ref* and *Sig* cameras prior to testing.

C. Digital Display P-BOS Imaging

As mentioned in Section II.A, there are two implementations of the LCD screen as the PO in the P-BOS system. The first is to remove the LS and CD, and use the built-in back-light of the LCD screen as the light source. The image in Fig. 10a shows the selective-region BOS result of the flow issuing from the nozzle of a canned air bottle. The speckle

pattern of the LCD can be seen projected onto the RBG, where the extents of this RBG board are denoted by the dashed red outline, and the mounts holding the RBG in place are outlined in dashed magenta. The circular aperture of the image is limited by the 50 mm optic mount for the PBS. The LaVision™ Random Pattern Generator software was used to create a PDF of the dot pattern, which was then displayed on a computer connected to the LCD screen via an HDMI cable. The nozzle density object is small compared to the dot size and spacing, but demonstrates the ability to use a built-in back-light for the speckle pattern projection.

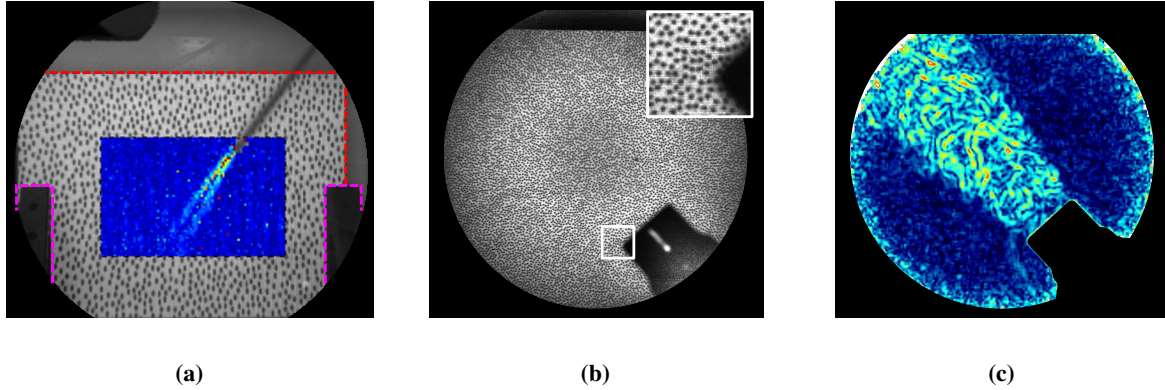


Fig. 10 (a) Canned air jet BOS result of built-in back-lit LCD projection. (b) Background-divided *Sig* image using transparent LCD speckle projection, and (c) resulting BOS pixel displacement magnitudes of a heat gun thermal plume.

The second implementation of the LCD system is demonstrated in Figs. 10b and 10c, where a heat gun thermal plume is now used as the density object. The back-lit LCD screen was replaced with a transparent LCD screen, and the LS and CD included in the system again. A 640 nm laser (Cavitar Cavilux™ HF) was used as the light source, and the speckle pattern was generated and displayed in the same manner as the previous LCD test, although this time with a different resolution. A background-divided *Sig* camera image is shown in Fig. 10b, with the inset showing the speckle pattern detail. When projecting from the LCD screen, the electrical lines between pixels can be seen imaged on the RBG, and so for this test, the FL focus ring was adjusted very slightly to de-focus these lines from the RBG while keeping sharp focus of the dots. The resulting pixel displacement BOS image of the heat gun thermal plume is seen in Fig. 10c, demonstrating equivalent signal quality as a physical PO, with the added benefit of quickly adjustable speckle patterns.

D. Shadowgraph Implementation

The P-BOS system was altered slightly (as discussed in Section II.B) to acquire shadowgraph images of the heat gun thermal plume. The heat gun and *Sig* camera were not moved from the P-BOS imaging of Section III.B. The iris aperture was included after the LS, and was closed to its smallest position. In this system, the CD lens was replaced with a longer, non-diffusing focal length lens (100 mm) due to the limited amount of light from the white LED after closing down the aperture. Had the laser light source been used instead of the LED, this switch would likely not be necessary.

A shadowgraph image of the thermal plume from the heat gun is shown in Fig. 11, where the heat gun has been masked for clarity, and the large circular mask denotes the edge of the projected light from the system. The thermal plume qualitatively matches the BOS results of the same heat gun in both Fig. 9 and Fig. 10c. The shadowgraph signal is slightly weaker however, due to its sensitivity to the second derivative of the density versus the first derivative of the BOS images. The ability to relatively easily switch to a shadowgraph system is made possible by the absence of a speckle pattern printed/sprayed on the RBG material itself, highlighting an important benefit of the P-BOS system.

E. 20-Inch Mach 6 Flat Plate Testing

The P-BOS system was to be used as a supplemental diagnostic during a test at NASA Langley Research Center's 20-Inch Mach 6 wind tunnel. Prior to bringing the system over to the tunnel, it was tested in a mock-up on an optical table in the laboratory. The expected throw distance between the FL and RBG was set, and the optics adjusted until the

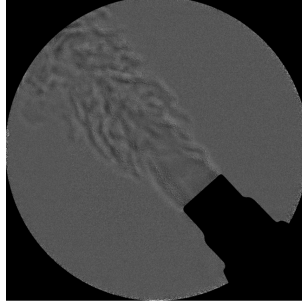


Fig. 11 Background-divided image of the thermal plume from a heat gun using the shadowgraph implementation of the P-BOS system, with a white LED for illumination.

desired focusing and magnification were achieved. An AF Nikkor™ 80-200mm 1:2.8 D lens was used as the FL, set to approximately 135 mm, with the aperture set to $f/2.8$. On the *Sig* camera, a 105 mm focal length relay lens (L^{Sig}) was used, set to an aperture of $f/11$ to provide a large depth-of-field. An extension tube was placed between this lens and the PCO™ Dimax HD camera to increase the magnification slightly to achieve the highest resolution images over the full-frame of the camera sensor.

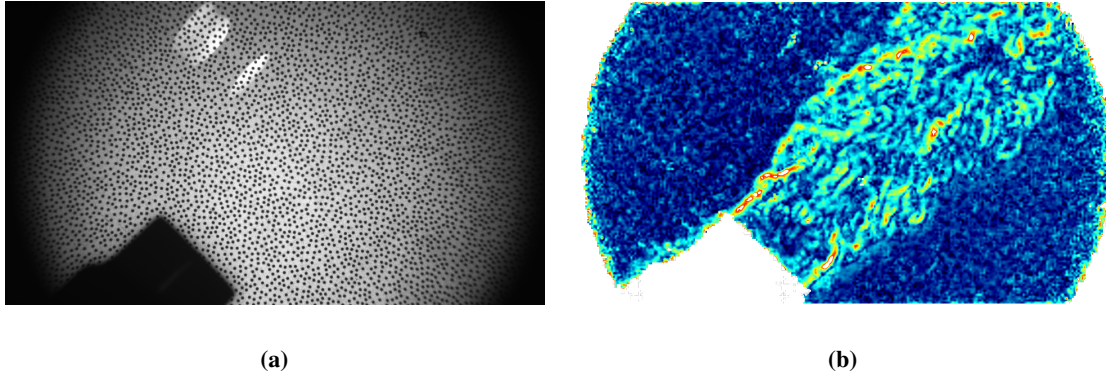


Fig. 12 Laboratory mock-up of the 20-Inch Mach 6 wind tunnel dimensions, imaging a heat gun thermal plume using the 0.2 mm PO, with (a) the raw image and (b) the pixel displacement BOS image, computed with the LaVision™ Davis 10 2D BOS module.

A raw image from the *Sig* camera is shown in Fig. 12a, where the heat gun nozzle is visible at the bottom left of the image. Both the projected speckle pattern and the heat gun nozzle are in sharp focus, demonstrating a good depth-of-field. The brighter regions near the top of the image are reflections from the front surface of the QWF, and can be seen to change position when the QWF is moved/adjusted. To eliminate this reflection, the QWF can be clamped flat to the RBG by using a flat piece of transparent acrylic, as was done for the tunnel testing discussed next. The pixel displacement BOS image from a single frame of the image sequence is shown in Fig. 12b, where the resolution of the turbulent structures of the thermal plume is reasonable. Regions near the edge of the field-of-view have larger displacements due to the lower signal-to-noise ratio.

An image of the polarized P-BOS system installed at the 20-Inch Mach 6 wind tunnel at NASA Langley Research Center is shown in Fig. 13, with appropriate labels included for most of the optics. The system is installed on the side opposite the model box access door, and so flow is from left to right. On the right (downstream) side of the P-BOS system is a self-aligned focusing schlieren system [33, 34] that was used to take simultaneous measurements of the flow over the flat plate with inclined ramp. Note that both systems use the same RBG/QWF, with the P-BOS system angled slightly downstream. The focusing schlieren system was the primary measurement for this testing campaign, and the P-BOS system was able to be used simultaneously because the RBG did not need speckling, which would have impacted the focusing schlieren measurement. The focusing schlieren measurement was angled at 45° relative to the freestream flow direction in order to be sensitive to both horizontal and vertical density gradients. This required the QWF to be oriented 45° relative to the focusing schlieren system, and so it was aligned with the RBG panel shown on the other side

of the test section in Fig. 13. Because the P-BOS system used for this test was the polarized version, it too needed to be rotated 45° for the appropriate polarization transformations through the system. The initial intent during setup was to use a beamsplitter and mirror combination (i.e., a periscope) to couple the P-BOS system into the optical axis of the focusing schlieren system, but time limitations did not allow for this. The P-BOS system was instead angled slightly relative to the window, aimed downstream. The ramp assembly on the flat plate was located right at the downstream edge of the window, and so the P-BOS system was not able to capture the ramp in the image, but instead imaged a region slightly upstream of the ramp.

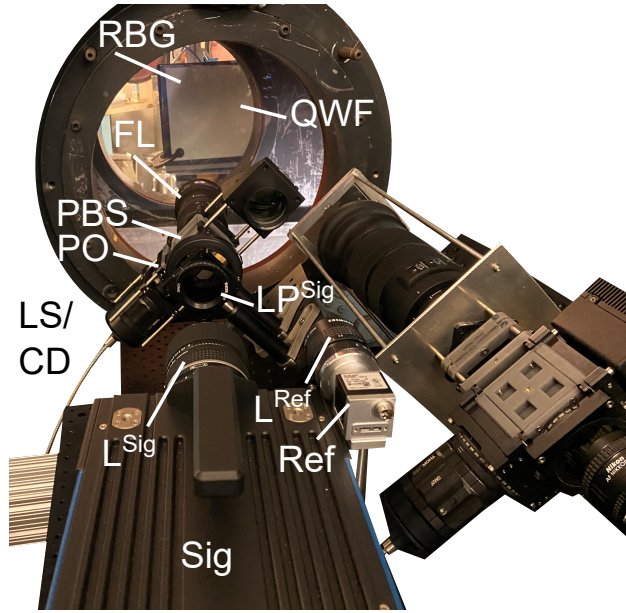


Fig. 13 Image of the P-BOS system installed at the 20-Inch Mach 6 wind tunnel next to the self-aligned focusing schlieren system. The P-BOS system is aimed slightly downstream in order to use the same RBG/QWF as the focusing schlieren system.

To initially demonstrate the system's operation when installed at the tunnel, a heat gun was used to provide a strong thermal plume density object. Without the model injected in the test section, the heat gun was introduced vertically, and an image sequence was acquired. A raw image of the heat gun positioned vertically in the test section is shown in Fig. 14a. Note that the imaging of the speckle pattern and the heat gun is not the same as in the mock-up data earlier in this section, since due to space limitations the system had to be altered slightly. With more setup time, the installed system could be adjusted to more favorable imaging conditions. A pixel displacement BOS image of the heat gun thermal plume is shown in Fig. 14b, using the LaVision™ DaVis software with a window/subset size of 39/13. The system remains sensitive to these strong gradients, but smaller-scale turbulent features are not as easily resolved due to the change in magnification of the system images.

P-BOS image sequences were acquired at a frame rate of 1 kHz during flat plate testing at various Reynolds number conditions, with different ramp angles. To avoid interference of the projected grid lines from the focusing schlieren and the projected speckle pattern from the P-BOS, the laser light sources and camera framing were offset during acquisition. A representative result from one run during this testing campaign is shown in Fig. 15. In Fig. 15a, a background-divided *Sig* image is shown, where the flat plate surface is visible near the bottom of the image. The background-division is performed by duplicating the image, applying a 50-pixel Gaussian filter, and dividing the raw image by this filtered image. This normalizes the intensity distribution of the image. It also allows the projected speckle pattern on the flat plate edge to be more visible near the bottom of the image. This is one of the side-effects of projecting the pattern onto the RBG; the speckle pattern will also be imaged onto the model. This does not interfere with the other measurements during this testing campaign, but it should be taken into account during measurement system design. The 0.2 mm PO was used for these measurements, although the dot sizes were deemed too large, and their spacing/density was too coarse. However, BOS results were still able to be obtained, as shown in Fig. 15b, where the pixel displacement from 100 images are averaged together (using a window/subset size of 39/13).

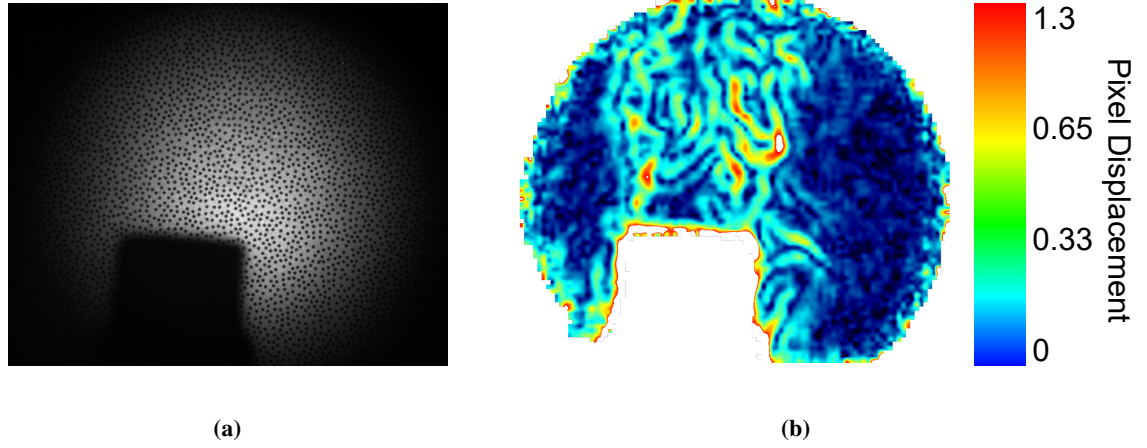


Fig. 14 Pre-test heat gun thermal plume testing with system installed at the 20-Inch Mach 6 wind tunnel, with (a) the raw image and (b) the pixel displacement BOS image.

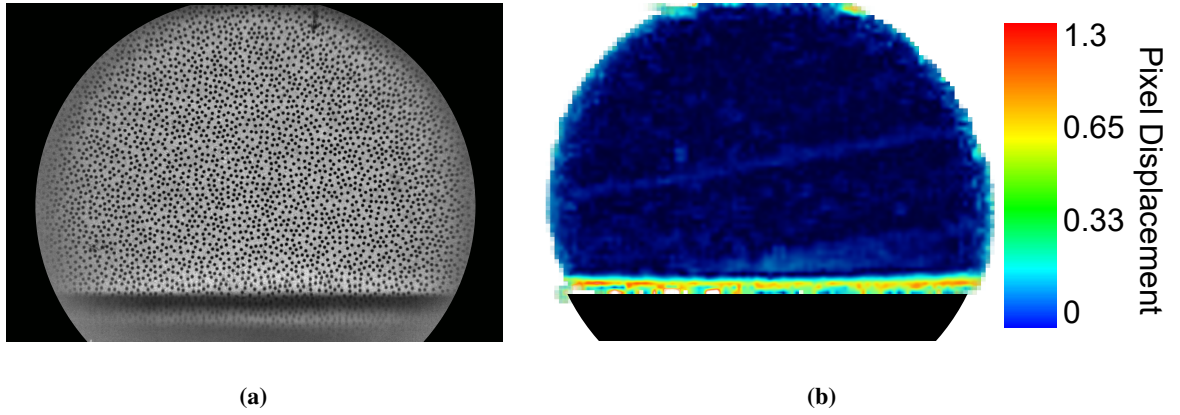


Fig. 15 Results from flat plate testing at the 20-Inch Mach 6 wind tunnel, with both the (a) background-divided *Sig* image of the projected speckle pattern and model injected, and (b) computed pixel displacement BOS image (100-image average) showing boundary layer, leading edge shock, and interaction region.

Flow in this image is from left to right, and several interesting flow features are visible. The first is the clearly defined boundary layer flow adjacent to the model surface (depicted in black at the bottom of the image). This boundary layer produces the largest pixel displacements. The second flow feature visible near the middle of the image is the shock wave produced at the leading edge of the flat plate. This angle is approximately 9.6° , which closely matches the expected Mach wave angle of 9.59° for a Mach 6 flow under isentropic flow conditions. The final flow feature visible is the interaction region produced by the influence of the ramp (downstream out of the field-of-view of the P-BOS system). This interaction region appears as slightly higher pixel displacements near the center of the image, just above the boundary layer edge. While these initial results are not highly-resolved due to the non-ideal dot pattern size/spacing for this particular setup, they instill confidence that this system can be refined for use as a practical diagnostic in wind tunnel facilities.

IV. Conclusions

A BOS system that uses a projected light speckle pattern instead of a physically-printed pattern has been developed. The system projects light through a patterned optic which is then split at a beamsplitter. Part of the light is used as a reference image, and the other is projected through the density object of interest and onto a retroreflective background, which is then imaged with a second camera. The speckle pattern can be adjusted by using different patterned optics, or

by changing the projected image on an LCD screen. By performing a pre-test transformation between the two camera images, a flow-off reference need not be acquired for the remainder of testing, allowing for changes to the speckle pattern during a test for optimization of the BOS signal. Because the background is not physically speckled with ink/paint/etc., the patterned optic can be removed from the system, and the system can be used to make shadowgraph measurements with minimal adjustments. This may be used when higher spatial resolution is desired. The polarized nature of the setup allows the system to be pointed at normal incidence to windows without imaging the typical window reflections or glare.

Laboratory demonstrations of the P-BOS system were performed to evaluate its equivalence to conventional BOS systems. The flow from a canned air jet and the thermal plume of a heat gun resulted in comparable images to conventional BOS. The system was then installed at the 20-Inch Mach 6 wind tunnel at NASA Langley Research Center to make measurements of the flow above a flat plate with a small-angle ramp. The field-of-view of the system was upstream of the ramp, since a focusing schlieren system was making measurements at the ramp. Nevertheless, three interesting flow features were identified in the P-BOS images, including a strong boundary layer, the flat plate leading edge shock (Mach wave), and the interaction region of the ramp and boundary layer.

Acknowledgments

This work was supported by the NASA Transformational Tools and Technologies (TTT) project. The authors would like to thank the NASA Langley 20-Inch Mach 6 tunnel staff, and Antonio Schoneich, Cole Sousa, and Greg Buck for their use of the flat plate model test time during their testing campaign. A provisional patent has been filed for the system discussed in this paper.

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