An Automatic Image Alignment Method Applied to Pressure Sensitive Paint Measurements

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ABSTRACT

Pressure Sensitive Paint technique (PSP) uses images that have to be processed to calculate the pressure field on the model. There are two main issues in image processing. The first one is to recognize the model position in the image and the second one is to use this result to extract the useful information from the image.

The presented method deals with these tasks. It requires markers on the model. They are filled circles that are detected with a dedicated function. They have then to be related to model markers. PSP technique provides a lot of images, so a software has been written to work in an automatic mode.

The camera attitude and location relative to the model are automatically recognized. The full software package enables to process PSP images without human involvement.

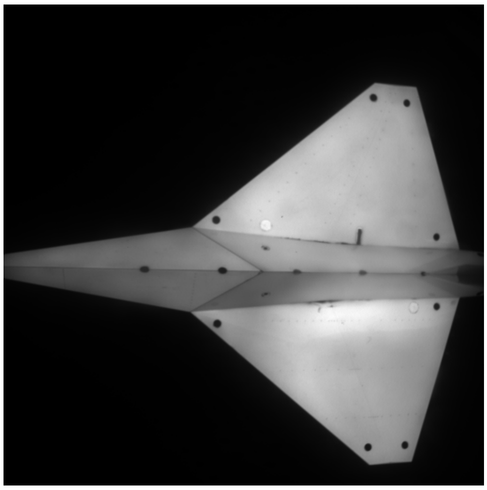

Figure 1: off1 reference image (DLR)

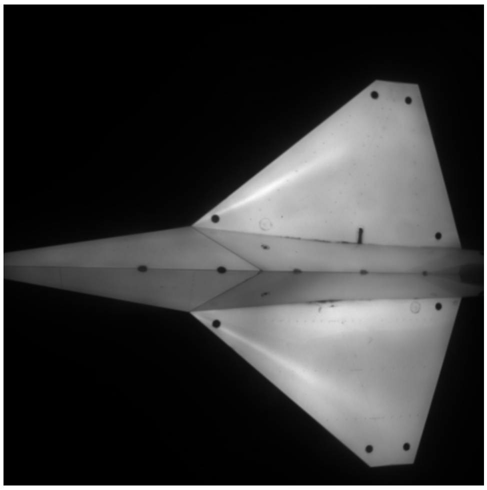

Figure 2: on1 test image (DLR)

INTRODUCTION

Optical mapping methods are now widely used in wind tunnels for measurements on the model or in the flow. They require to apply a data reduction method that includes image processing. From this point of view, Pressure Sensitive Paint method (PSP) is a demanding technique.

PSP [1] is used to measure pressure on a model mounted in a wind tunnel. It should enable to reduce or suppress the usual equipment made with pressure taps. This will save cost and time while giving more information about the pressure field on the model. ONERA develops its own system for its industrial and research tests [2].

Most of PSP methods perform a ratio between a reference image (like off1 in figure 1) and the test image (like on1 in figure 2). But the model is not exactly at the same location in these two images. This occurs because of model deformations, wind tunnel deformations or displacements of the camera. The ratio looks rather rough without correction like in figure 3, so the test image has to be aligned on the reference image before ratioing. This alignment must be done with high accuracy because the final quality of the pressure mapping depends greatly on it.

Another feature of PSP is that it provides a lot of images, one per test condition. Therefore the alignment has to be done a lot of time. The point is the time consumed by an human involvement. Actually, this requires to design an automatic alignment method. It should be noted that this is hardly addressed in PSP papers.

A marker detection method and an automatic alignment method are described hereafter. Recognition of the Camera Attitude and Location (CAL) relative to the model is addressed briefly because it has been already presented in detail at the 16thICIASF [3].

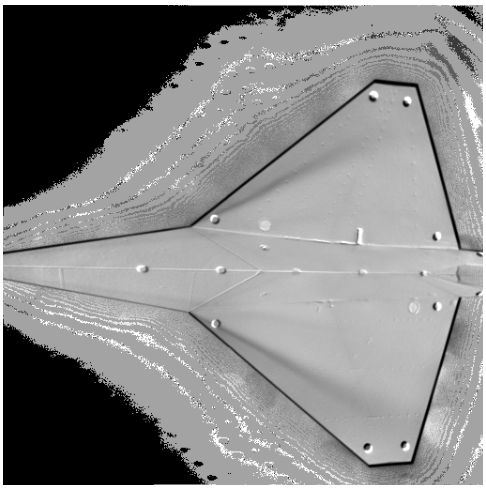

Figure 3: ratio off1/on1 without alignment

COMPONENTS OF AN AUTOMATIC DATA REDUCTION METHOD

The method has been designed for PSP measurements but it could also be applied to other optical methods like infrared thermography [4] for heat flux measurements. Its main components are:

+ an automatic alignment method,
+ an automatic CAL identification method,
+ extracting information using the identified CAL.

The alignment method itself includes two items that are discussed hereafter:

a) An automatic method to recognize the marker positions in the image.
b) An automatic method to link the markers in the test image to the markers in the reference image.

After the steps a) and b), the alignment is done with a polynomial transformation. This could introduce defects outside the area where the polynomial transformation has been defined. For higher accuracy, the alignment could occurs after the CAL has been identified. Afterwards, the ratio takes place. The paper is focused on the automatic recognition method and on the automatic linking method. The CAL identification method and data extracting are briefly reported. An example is used as a guideline to present the developed tools.

AUTOMATIC ALIGNMENT

Presentation with an example

As ONERA, DLR develops its own system [5]. As a part of the cooperation between DLR and ONERA, a DLR's PSP test has been selected to illustrate how the method works. This is a test on a 3D full model. off1 image in figure 1 is a reference image without wind. The markers are clearly visible and are quite large, nearly 8 pixels. There were made with a material that is insensitive to pressure so they are quite black.

Figure 2 is a test image on1. The ratio off1/on1 is presented in figure 3. The edge of the model is thick and black, the markers are black and white and the pressure taps are visible. This means that the model motion is small but is not negligible, nearly 3 pixels. The ratio can be converted in pressure according to a calibration curve, but figure 3 provides only a rough pressure field because of the model motion.

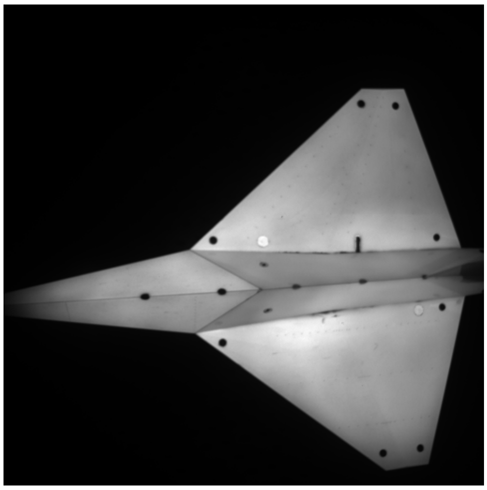

Figure 4: off2 reference image (DLR)

Figure 4 is an other reference image off2 with the model in yaw. The rotation of the model has to be corrected before to extract data. That needs to recognize the attitude of the camera (CAL).

Recognition of image markers

A tool that recognizes the image markers had to be written. Many ideas were tested and the more efficient has been selected. It is a function called Spot that detects holes of an user defined size. It models the gray level g around the current pixel with a plane and a hole according to the following expression:

$$g_f = g_0 + g_l\,\delta l + g_c\,\delta c + h_f\, f\left(\sqrt{\delta l^2 + \delta c^2}\right) \qquad \textbf{(1)}$$

where g_f is the assessed gray level, g_0 is the local average level, g_l and g_c are the local slopes, δl and δc are the coordinates relative to the current pixel and f is a function that describes the shape of the hole. The depth of the hole is the h_f parameter. g_0, g_l, g_c and h_f parameters are assessed with a root mean square method. The working area should be a circle with a radius equal to twice the radius of the markers r (see figure 5). The f function can be selected in a set of functions. Three of them are presented in figure 5. Basically the simplest one is used, i.e. the inverse top hat shape.

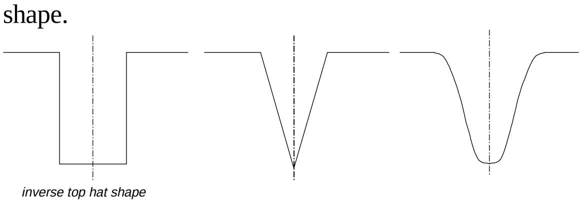

Figure 5: three examples of hole shapes

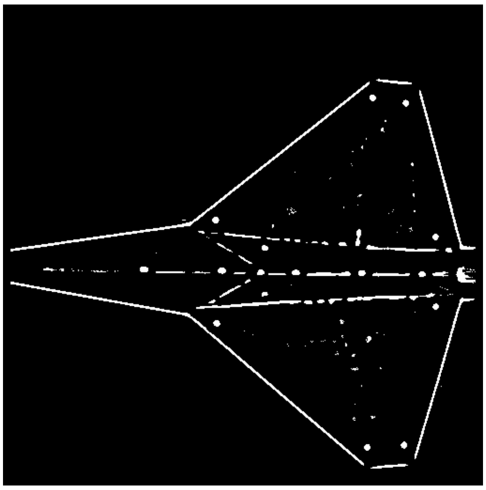

Figure 6: off1 merit image with $h_f > 5$

Spot computes the least square error E_f as:

$$E_f = \Sigma(g - g_f)^2 \quad \textbf{(2)}$$

A good marker should have a high value for h_f and a small value for E_f. But E_f could be small without marker. A merit parameter m_f is used to overcome this:

$$m_f = \frac{E_f}{h_f} \quad \textbf{(3)}$$

m_f is small for good markers and increases for paths which are not holes. A value of 1 for m_f means that the volume error is like the volume of the theoretical hole.

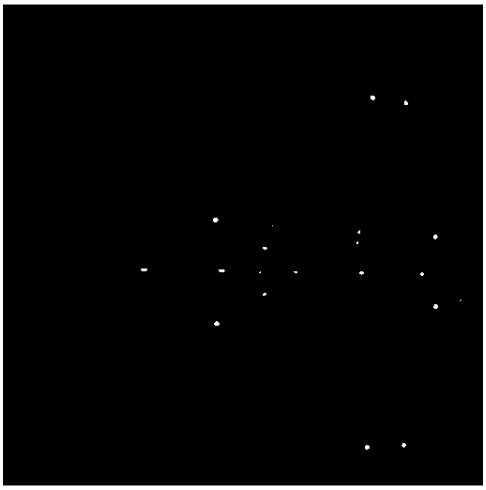

Figure 7: off1 merit image with $m_f < 1$

The two parameters h_f and m_f are used to detect markers. Basically h_f should be greater than 5. This value is sufficient to eliminate small defects that could be understood as markers. Real markers, like in figure 1, have a greater value so they are not eliminated by this threshold.

Figure 6 shows what happens with the off1 image. As expected, the markers are detected but other parts of the model are also detected. They are part with high gray level gradient, so the h_f value is high even if the error E_f is high. These defects are eliminated while thresholding with the merit factor m_f at 1. Figure 7 shows that the markers are detected without doubt. Their centers are calculated and they are superimposed on off1 in figure 8.

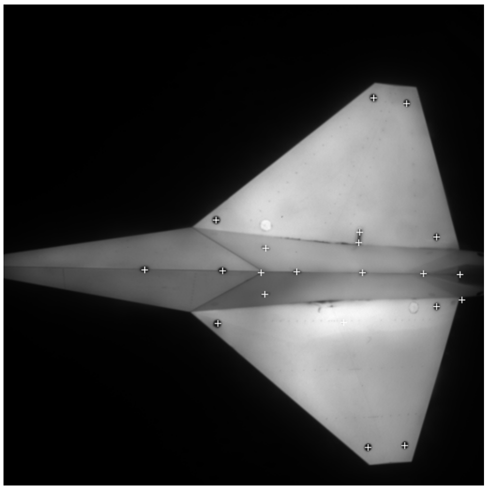

Figure 8: off1 image + detected markers

The same work was done on on1 and figure 9 was obtained. Extra markers are detected that are defects in the paint itself. The linking method will eliminate them.

The detection depends on the assumed radius of the markers. Figures 6-9 were obtained with a radius of 4. If a radius of 1 is used, a lot of things can be seen, like pressure taps in figure 10. Pressure taps were selected in figure 10 and are superimposed on off1 in figure 11.

The accuracy depends on the quality of the image and of the quality of the markers. It is basically 0.1 pixel for good images like off1.

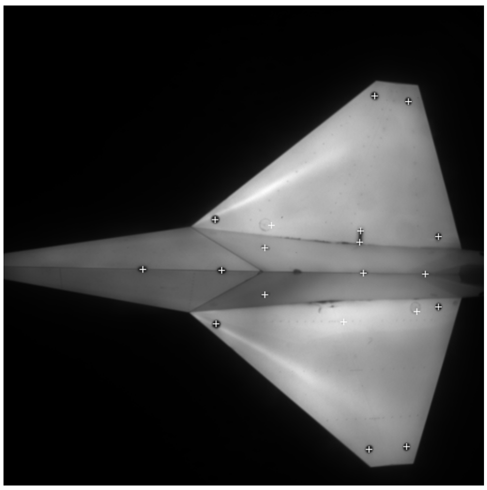

Figure 9: on1 image + detected markers

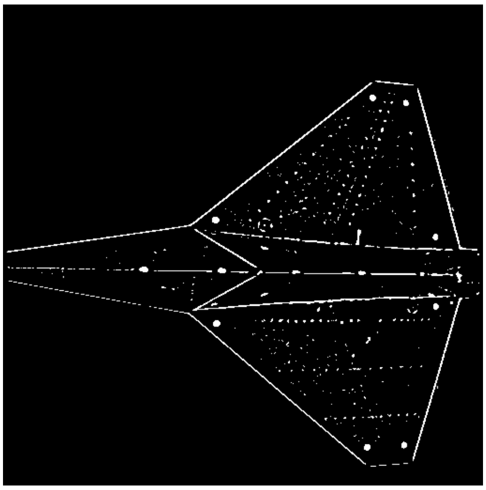

Figure 10: off1 merit image with hole radius = 1 (pressure taps)

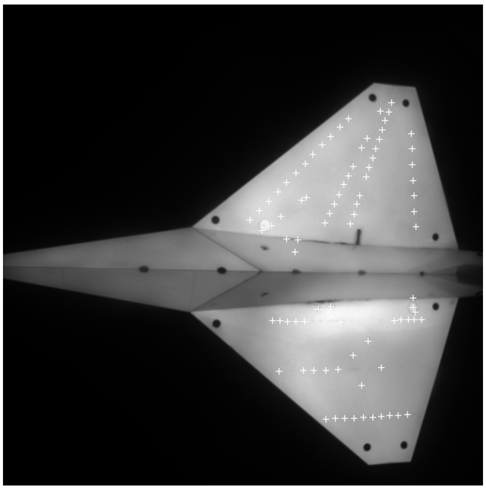

Figure 11: off1 image + pressure taps

Linking of markers

It remains to link the markers in off1 (figure 8) with the markers in on1 (figure 9). This is quite easy with these images, but this is rather difficult with the off1 image and the off2 image because the model movement is large.

The first trial was based on a distance criterion. The idea was to link a marker in the first image to the nearest marker in the second image. This very simple method worked well for small motion like off1-on1 but it failed for large motion like off1-off2. It inverted the markers at the tip of the wings, so it was unable to link properly the markers.

A more advanced method has been designed. Its principles are the following:

+ 3 markers are selected in the first image They should cover a large part of the model.

  Then occurs a loop:
+ An assumption is made to link each of the 3 markers to a marker in the second image.
+ A polynomial transformation of the first order is assessed according the two sets of markers. This transformation links the two sets and provides a kind of image deformation.
+ The polynomial transformation is applied on all the markers in the first image. Obviously the 3 selected markers becomes the linked markers in the second image. The other markers are projected in the second image.
+ The nearest markers of the projected markers are selected. So all the markers in the initial image are linked to markers in the second image.
+ The distance between the projected marker and the linked marker is computed. Then only pairs of markers with a distance under a given value, basically 5 pixels, are selected. These pairs are counted.

The idea is quite simple: if the assumption to link the third markers is good, the number of selected pairs will be high. All the possible assumptions are checked and the one that provides the higher number of linked pairs is claimed to be the linking solution. Figure 12 presents this method.

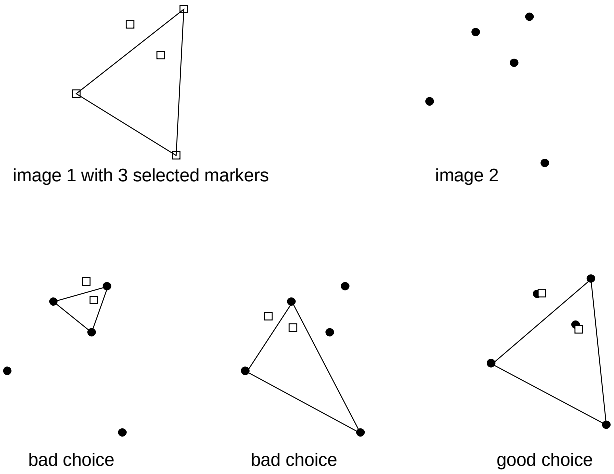

Figure 12: principle of the linking method

In fact this works very well. Most of the assumptions provide only 3 pairs and only a few of them give more than 4 pairs.

In most cases, like the presented one, there is only one solution. But there are cases typically with a symmetrical distribution of markers that provide more cases up to 4. They are obtained by rotating and inverting the markers. A refinement is used to select the good solution. This one should minimize the scale change and should looks like a rotation in the image plane. This method was applied to all the available cases and the right result was obtained.

Alignment

Since the reference and the test images are linked, it is possible to compute a polynomial transformation that links the two sets of markers. The order of the polynomial transformation could be 1 up to 3. The order 2 requires 6 markers, and the order 3 requires 10 markers. Extra markers are managed with a least square method.

The polynomial transformation is applied to each pixel in the test image. An aligned image is obtained. It is used to perform the ratio with the reference image. Figure 13 shows the ratio off1/on1 obtained with the order 3. This image should be compare to figure 3 without alignment. The pressure taps are hardly visible and the image looks very fine. Figure 14 shows the ratio off1/off2. This demonstrates that the alignment works very well even for large model movements.

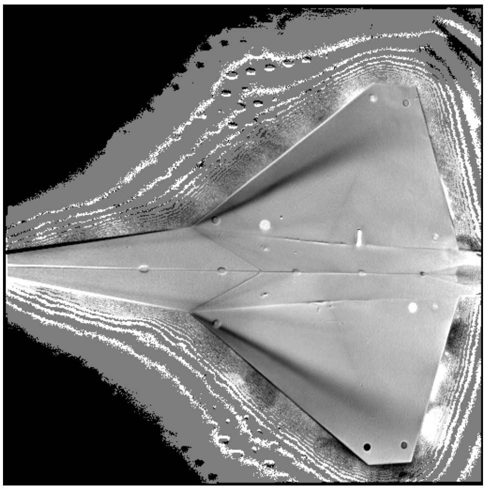

Figure 13: off1/on1 ratio with alignment

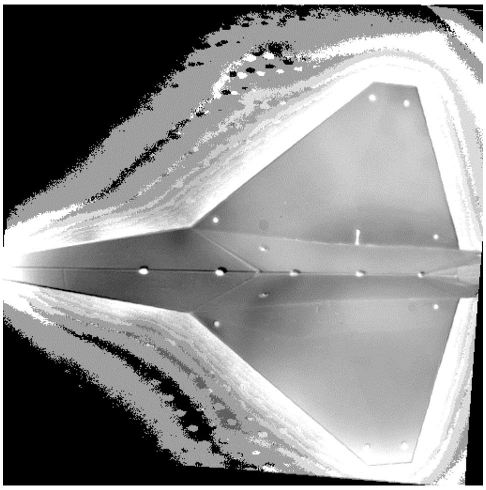

Figure 14: off1/off2 ratio with alignment

Alignment with pressure taps

Pressure taps can be used as markers when there is a lack or model markers. They were detected with Spot and the selected pressure taps, about 70, are presented in figure 11 on the off1 image. Spot was applied on on1 and this produces about 300 markers like in figure 10.

The linking method was applied and nearly all the 70 pressure taps were linked in off1 and on1. The alignment was then performed with a polynomial transformation of the third order. The resulting image looks very similar to figure 13. That means that small details on the model could be used as markers.

Relation of image markers and model markers

It is required to relate image markers to model markers in order to extract data from the final images. This is actually a result of the linking step.

Markers in the reference image must be selected so that it remains only markers that exist on the model. The remaining markers are related to markers on the model. This can be done with an user friendly software.

The linking method links markers in the test image to markers in the reference image. As these have been related to model markers, markers in the test image are also related in turn to model markers.

The problem is to relate the reference image to the model. Fortunately this one could also be linked to an other reference that has been related to the model. Therefore the human involvement to relate markers in the reference image to markers on the model is required only the first time.

CAMERA ATTITUDE AND LOCATION

The camera attitude and location (CAL) can be described with 6 parameters that are 3 rotations and 3 translations. Figure 15 shows how these parameters are ordered. A minimum of three markers are required to evaluate them. The relation between the parameters and the position of the markers is highly non linear. That requires to use a dedicated tool able to identify the CAL. This tool starts with an initial estimate and improves it with an iterative method. The usual least squares method is applied to assess the quality of the CAL and to cope with extra markers.

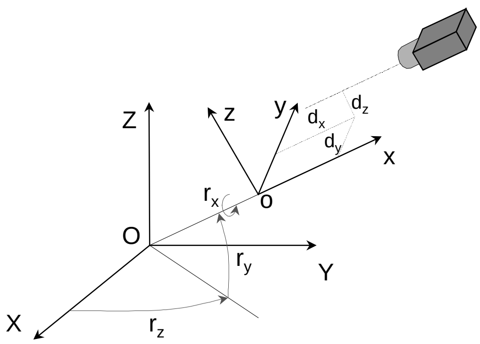

Figure 15: camera attitude and location (CAL)

When the CAL has been obtained, it is checked by superimposing on the image the edge of the model, like in figure 16. A grid of the model is used for this purpose. The CAL includes some characteristics of the camera, like the focal length and the CCD size. It is also possible to correct for optical defects providing a calibration has been made. More details about CAL and its management can be found in [3].

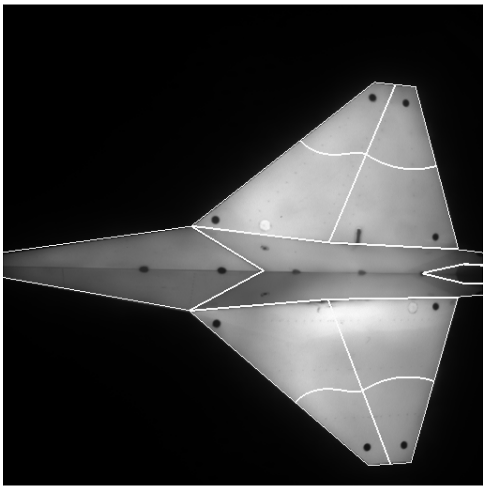

Figure 16: off1 + model edge

RESECTION

The CAL enables to relate a point on the model to a pixel in the image. It is also possible to relate each pixel to a point on the model. So comes the idea of getting information off the image to make cut lines or to create images that could be obtained with an other CAL.

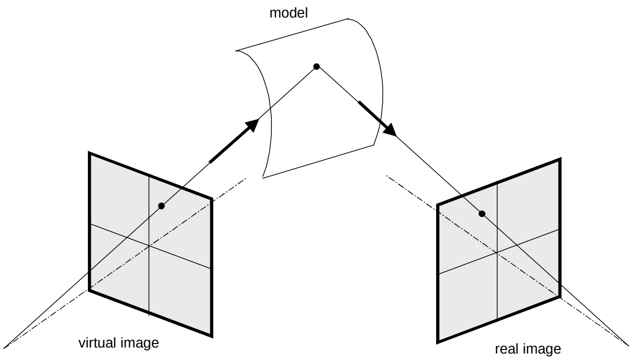

Figure 17: principle of the resection method

This is much more than alignment, and even more than what is usually understood with the restrictive term "registration". Bell and McLachlan [6][7] introduced the medical term "resection" for this kind of image processing.

The ONERA's resection method [3] works as follows:

+ The grid of the model is build with triangles. Each triangle projects into a triangle in the image. This establishes a relation between the grid triangle and the image triangle. By inverting this relation, one obtains a relation between each pixel with a point on the model grid.
+ Cut lines can be made easily by using the relation between point and pixel.
+ Virtual images can be created. For a virtual CAL, each pixel in the virtual image can be related to a point in the grid and this point can be related to a pixel in the initial image. This principle is described in figure 17.

RESECTION AND ALIGNMENT

The resection method can be used to process the test image. A virtual test image is created according to the CAL of the reference image. The resulting image can be used to perform the ratio with the reference image.

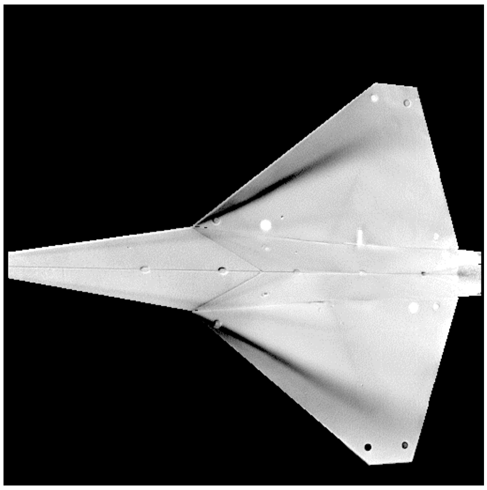

Figure 18: off1/on1 ratio with alignment and resection

Figure 18 presents this ratio for the off1 and on1 images. This figure should be compared to figure 13 obtained with a polynomial transformation. They look very similar except at the wing-fuselage junction where resection provides higher quality. This is due to the fact that resection uses the 3D features of the model while the polynomial transformation may introduces defects between markers.

Figure 19 shows the ratio of the off1 and off2 images. The improvement appears more clearly when comparing with figure 14. The improvement is highlighted on the fuselage because of its 3D feature.

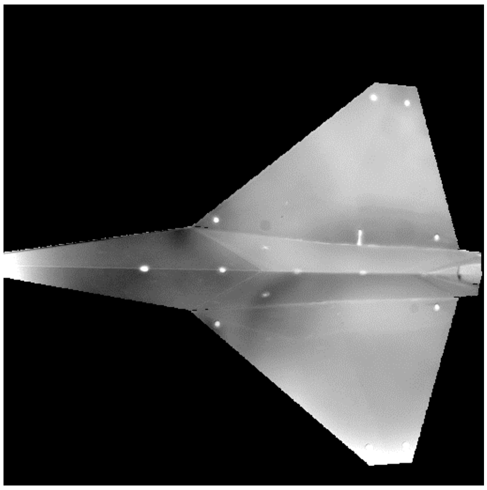

Figure 19: off1/off2 with alignment and resection

The improvement provided by resection is more impressive if there are a few markers or if they are misplaced. Let's consider off1 (figure 1) where only the 4 markers on each wing and the 2 left hand side markers on the fuselage are selected. These 10 markers enable to use a polynomial transformation of the third order. This transformation applied to off2 (figure 4) produces the aligned image in figure 20. The resulting alignment looks bad even if it is good close to the selected markers. This is the effect of interpolating (between markers on the wings and the fuselage) and extrapolating (on the upstream part of the model) with high order polynomial transformation.

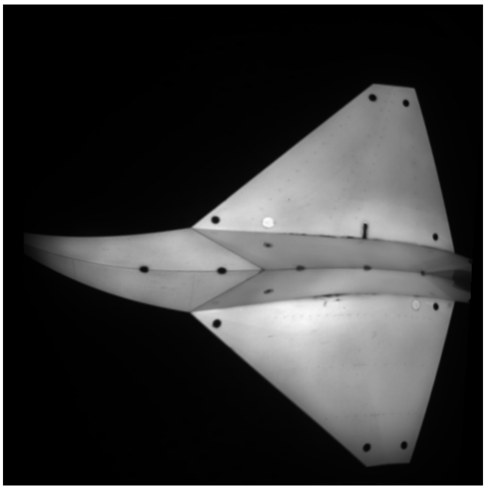

Figure 20: off2 aligned image with 10 markers

There is no sense in using figure 20 to perform the ratio off1/off2. This should be compared with the alignment using resection which produces a ratio image like figure 19 without defect. As a consequence the best alignment is obtained by combining the automatic detection and linking methods with the resection method.

AUTOMATIC PSP DATA REDUCTION

The actions for automatic PSP data reduction are:

for the first reference image:
+ Automatic detection of the image markers with Spot.
+ Selecting the markers that can be related to real markers on the model.

for the current reference image:
+ Automatic detection of the image markers with Spot.
+ Automatic linking with the first reference image. The linked markers are then also related to model markers.
+ Automatic CAL recognition.

for the test image:
+ Automatic detection of the image markers with Spot.
+ Automatic linking with the current reference image. + Automatic CAL recognition.

for the PSP data reduction:
+ Resection of the test image according to its CAL and the CAL of the current reference image.
+ Ratioing of the resected test image and the reference image. The ratio can be convert into pressure using a calibration curve.

Obviously the data reduction method depends on the PSP method. It may use more than 2 images and even use in situ calibration with pressure taps. All these actions can be done in an automatic mode.

Finally the data are extracted from the final pressure image. It is also possible to create virtual images, like in figure 21. These images can be useful to highlight a flow pattern or to combine several images.

LIMITS

The presented method is currently limited only within the linking method. This one links markers with a polynomial transformation and problems may occur for large movement with 3D models, because a polynomial transformation is not able to represent 3D motion in a right way.

This problem has not yet been encountered, but it could appears. It has been simulated using the resection method and some work has to be done. The best solution is to keep using image processing tools. If this does not succeed, an usual solution could be used. The simplest one is to link with a previous test image, assuming that the model motion remains small.

Figure 21: virtual 3D view off the ratio off1/on1

CONCLUSION

PSP method is going to be used intensively in industrial wind tunnels. This requires to use an automatic data reduction method. Such a method has been designed at ONERA. The method detects the image markers, links them to markers in the reference image and relates them to model markers.

The alignment can be performed with a polynomial transformation, but it has been demonstrated that the alignment using the resection tool is more reliable. It takes into account the 3D features of the effect while the polynomial transformation may introduce errors.

The linking step can be improved but it works well enough to be used for usual tests. Wind tunnel teams can now use the PSP method while focusing on aerodynamics and measurements, not on data reduction.

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