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A Qualitative Review of Selected Infrared Flow Visualization Processing Techniques: Contrast Enhancement and Frequency Domain Analysis

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The deployment and integration of high-sensitivity infrared cameras in a transonic wind tunnel test environment has resulted in a unique capability to image aerodynamic phenomena in real-time. Multi-camera infrared flow visualization data systems are now routinely utilized at the NASA Ames Unitary Plan Wind Tunnel. The small flow-induced temperature gradients on the surface of the wind tunnel test article coupled with the high bit-depth of the infrared camera sensor makes the processing of the image data critically important. An image processing routine must enhance features of interest with minimal artifacts. Additionally, the production wind tunnel test environment demands that these processed images are made available in a real-time, automatic fashion. Therefore, any image processing routine must be computationally economical and enhance the image data with minimal input from a human operator. The following seeks to qualitatively explore selected image processing techniques by assessing their effectiveness to resolve flow features on a wind tunnel test article. A multi-scale contrast enhancement technique is introduced as well as a new implementation of a multi-scale, non-interpolated adaptive histogram equalization. Finally, a novel method is introduced that demonstrates the ability to resolve flow features imaged on bare-steel test articles possessing low emissivity. This method merges frequency domain analysis with contrast enhancement and has the potential to extend the application of infrared flow-visualization within the wind tunnel test environment.

I. Introduction

The deployment and integration of high-sensitivity infrared (IR) cameras in a transonic wind tunnel test environment has resulted in a unique capability to image aerodynamic phenomena in real-time. Multi-camera IR flow visualization data systems are now routinely utilized at the NASA Ames Unitary Plan Wind Tunnel (UPWT). The small flow-induced temperature gradients on the surface of the wind tunnel test article coupled with the high bit-depth of the IR camera sensor makes the processing of the image data critically important. The following discussion uses a reference set of images to compare various image processing approaches. This reference image set is of a wind tunnel model in the 11-by-11 foot test section of the NASA Ames UPWT at a Mach number of 0.95. This test article has been painted with a high-emissivity (~0.88) coating for the purposed of IR flow visualization. This image was acquired by a FLIR SC8203 mid-wave IR camera whose sensor possess a depth of 14-bits per pixel. To view this image through most human machine interfaces, it is necessary to rescale each pixel from 14-bits to 8-bits. Upon examination of the histogram (Figure 1) of a raw image it is apparent that this is not a straight forward task. Typically, the histograms of the unprocessed, 14-bit images are not normally distributed and contain a wide dynamic range. A flow feature driven temperature gradient may only be on the order of tens of counts and consequently will be hidden within the large dynamic range of the image. Classically, the task of enhancing features within an image falls under an image processing class known as contrast enhancement. Often times this results in an image whose histogram bins have been more evenly distributed across the display range. An image processing routine must enhance features of interest with minimal artifacts. Additionally, the production wind tunnel test environment demands that these processed images are made available in a real-time, automatic fashion. Therefore, any image processing routine must be computationally economical and enhance the image data with minimal input from a human operator. The following seeks to qualitatively explore selected image processing techniques by assessing their effectiveness to resolve flow features on a wind tunnel test article. A multi-scale contrast enhancement technique is introduced and compared with a non-interpolated adaptive histogram equalization method.

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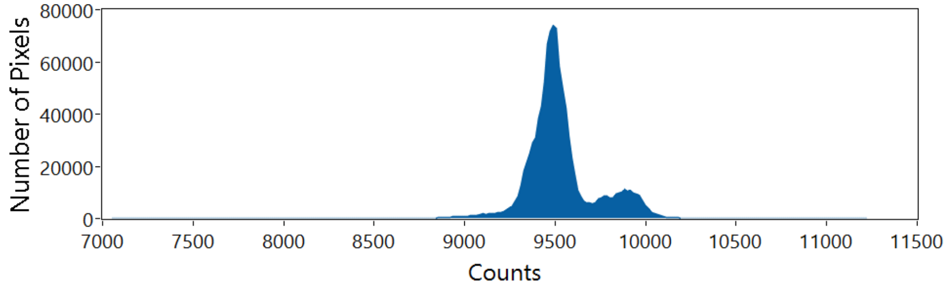

Figure 1: Raw IR image histogram (14-bit Pixel Depth)

Figure 2 depicts an 8-bit linearly rescaled image (left) whose original histogram is detailed in Figure 1. In the following discussion this image will be used as a reference to compare image processing techniques. The rescaling (left) performed is linear so that the shape of the original histogram is preserved. The outline of high contrast features are visible. These features are mainly related to model geometry (wings and tail), as well as the wind tunnel test section slotted walls. Some hints of flow driven features can be seen near the leading edges on the surface of the wing, however the lack of contrast makes them difficult to resolve. A common method of contrast enhancement known as global histogram equalization is depicted in the right-hand image of Figure 2. Global histogram equalization is an automatic process that attempts to equally distribute the bins of the original histogram across the final rescaled bit range. When compared visually with the linearly rescaled image the equalized image contains more contrast and its histogram has been radically transformed. Flow induced temperature gradients at the leading edge of the wing, tail, and engine fairings are now evident. However, the fine spatial detail is lost in the oversaturation of the image.

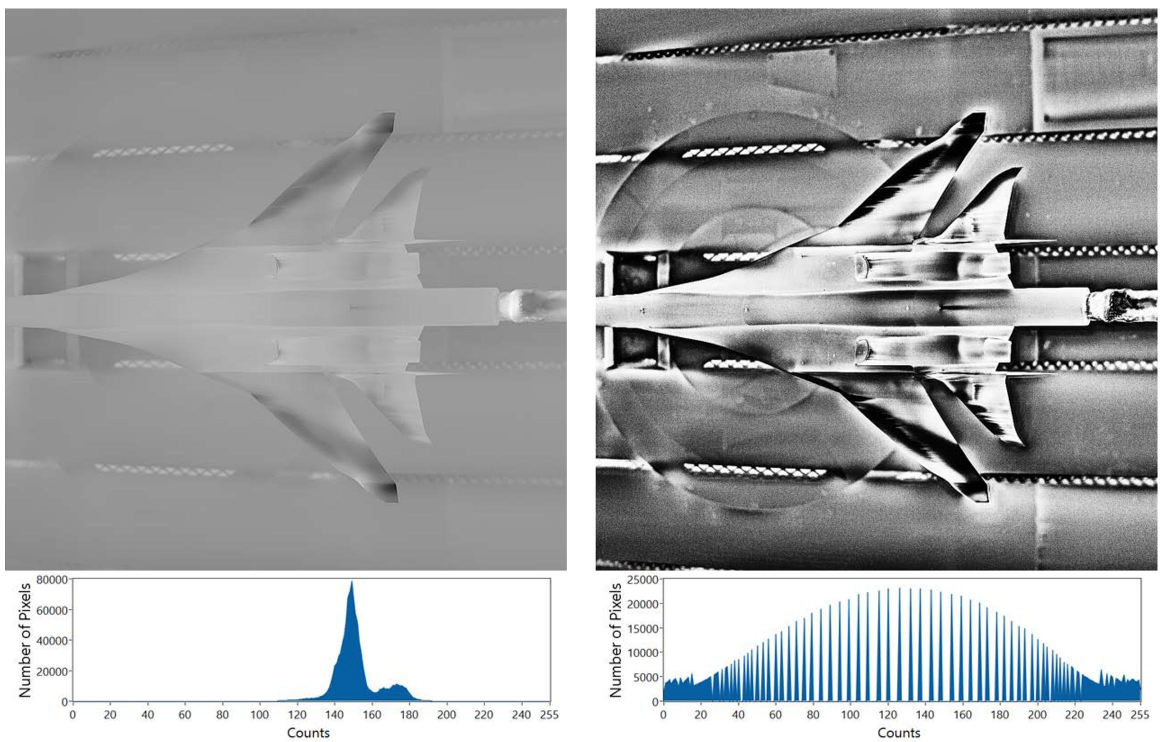

Figure 2: "Reference" IR image, 8-bit linear rescale (left) versus global histogram equalization (right)

A contrast enhancement technique known as adaptive histogram equalization (AHE) performs the histogram equalization operation within a fixed sized window that is convolved across the image. There are several implementations of this method, some reduce noise in uniform regions by limiting contrast (CLAHE), most reduce compute time by equalizing within fixed sub regions and interpolating look-up-table values between. With high dynamic range images, the interpolated AHE implementations can cause artifacts in regions with sharp pixel value gradients. The implementation of AHE discussed here is non-interpolated (the equalization sub windows is convolved pixel by pixel across the entire image) to avoid these artifacts. Figure 3 compares two methods of AHE processing performed on the previously discussed reference image. The left-hand image has been processed with a sub-region of 128-by-128 pixels (1/8x1/8 total image size). Qualitatively the contrast of the image has been improved while the small scale flow features have not been over-saturated. However due to the fixed size of the sub-region the scale of the features that are enhanced do not exceed the size of the sub-region. Even with the non-interpolated AHE implementation image artifacts can still arise. Like the interpolated method this happens in areas of high gradients where the sub-region spans a large dynamic range. Often this is manifested as a light or dark halo effect around the edges of the test article. A slight halo effect can be seen in the left-hand image of Figure 3 near the leading edge of the wings. To address the shortcomings of a fixed scale AHE implementation a multi-scale AHE method is proposed, whose results can be seen in the right-hand image of Figure 3. In this multi-scale method two fixed regions are used to process the original image. One region is intended to enhance large-scale features using a large sub-region (in this case 256-by-256 pixels), while a second small region is used to enhance small-scale features (in this case 32-by-32 pixels). The result is two separately enhanced images, that are then blended to produce a single image. This multi-scale AHE method produces good quality results with minimal halo artifacts but is computationally expensive as the AHE method (computationally expensive in its own right) is performed twice.

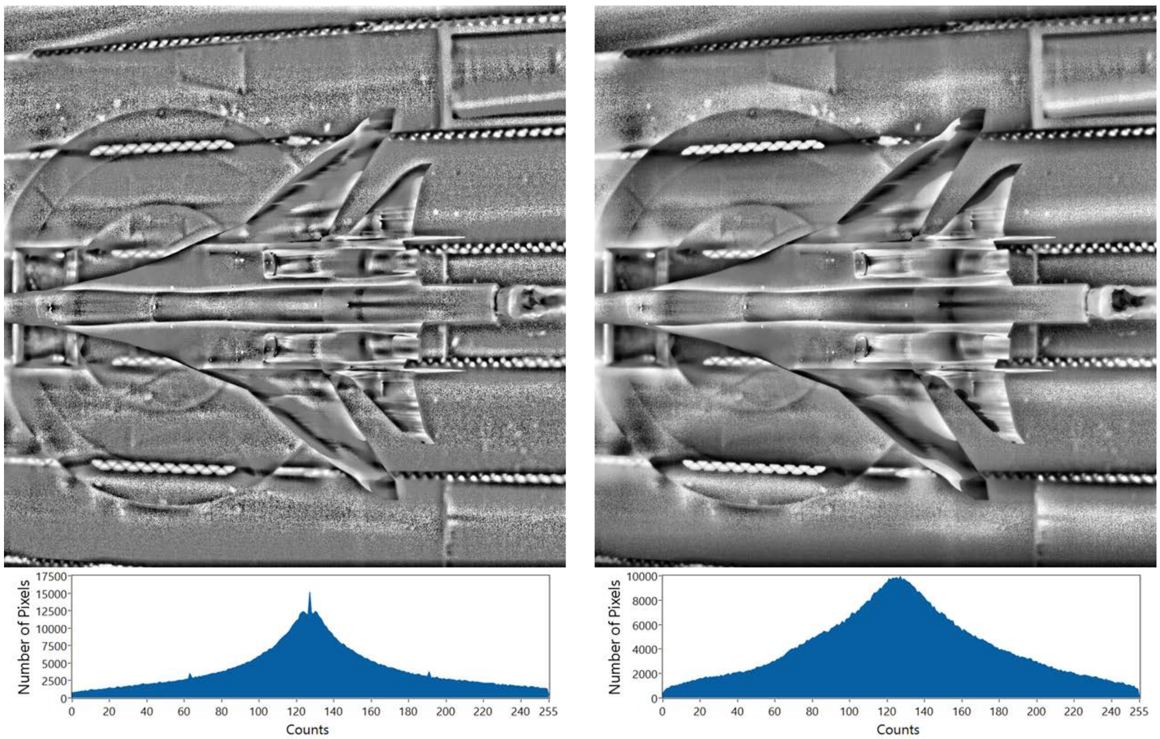

Figure 3: Adaptive histogram equalization, single-scale (left) versus multi-scale (right)

Upon considering the single-scale and multi-scale AHE techniques it is apparent that choice of spatial scale is important. To that end a method is presented to perform contrast enhancement across several spatial scales in a manner that is computationally efficient. The Laplacian pyramid is a method of decomposing an image into a multi-level set of spatially filtered band-pass images. Here it is proposed to extend this to a method of contrast enhancement based on the following: The histogram at each band-pass image level is generally normally distributed and centered about zero. Consequently, it is straight forward to normalize each image level based on the standard deviation of its histogram (Figure 4). Each level can then be weighted, and the pyramid reconstructed to produce an enhanced image (Figure 5). This method seems to produce a nice-looking image that is low in noise and able to simultaneously enhance many spatial levels of detail in the image (Figure 6). Additionally, the resulting image is generally artifact free and can be computed quickly as the decomposition is based on a set of separable filters that can be vectorized.

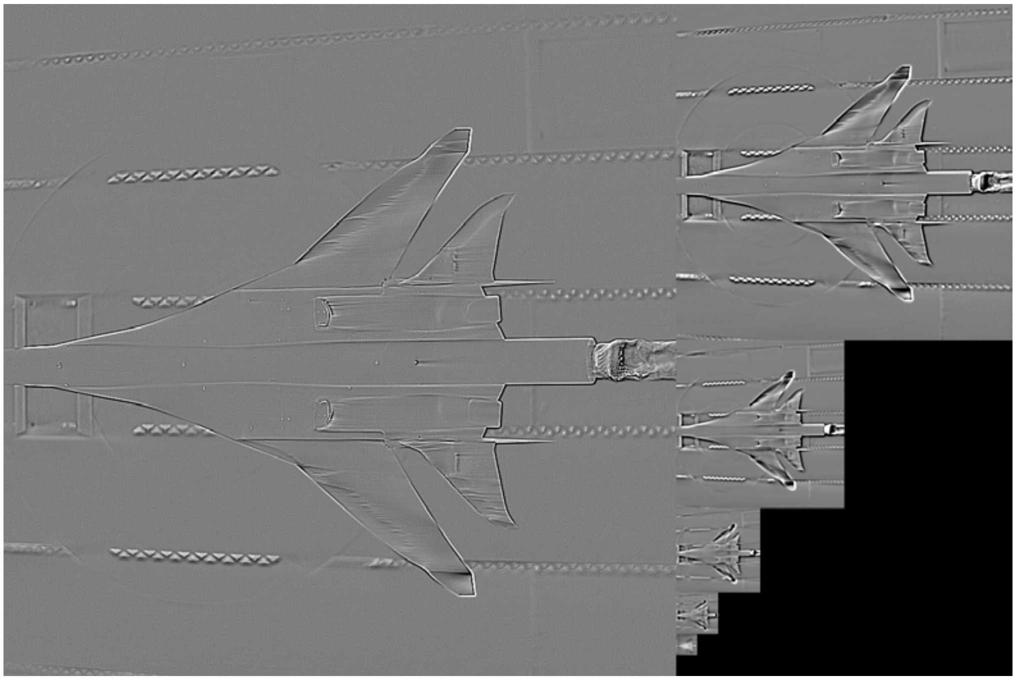

Figure 4: Normalized Laplacian pyramid decomposition (six band-pass levels)

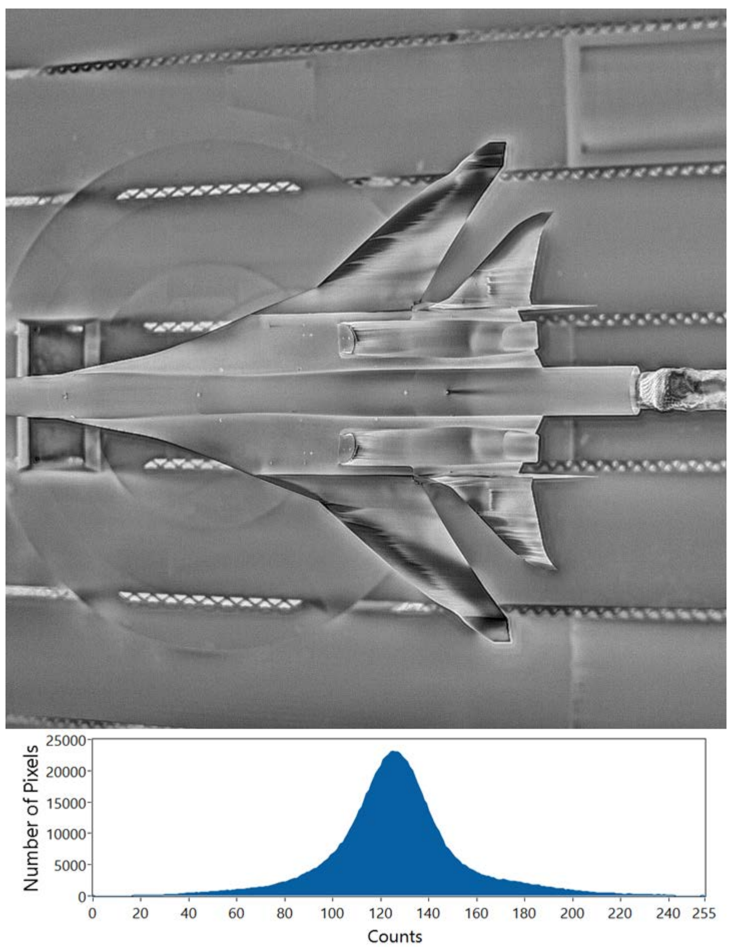

Figure 5: Normalized Laplacian pyramid reconstruction

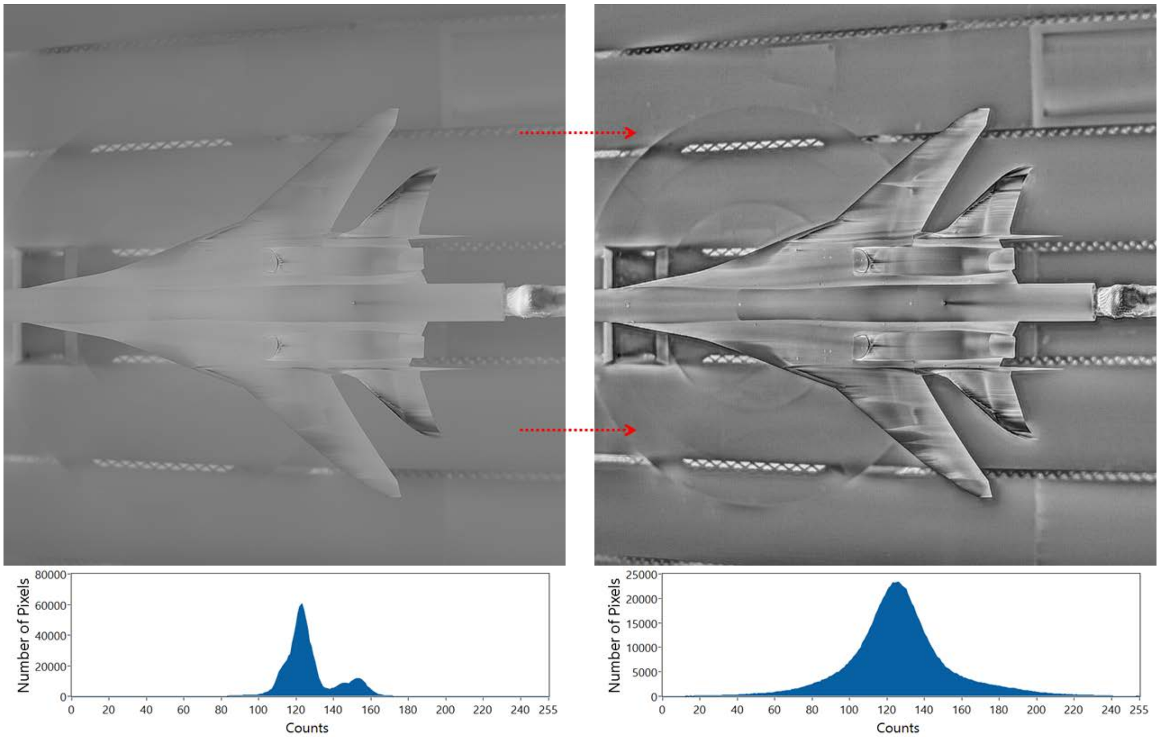

Figure 6: Linear rescaling versus normalized Laplacian pyramid reconstruction (Mach = 0.95, α = 5º)

The following outlines a technique to use frequency domain analysis and filtering in conjunction with contrast enhancement to process infrared datasets. This technique is able to reveal low signal strength flow phenomena and is well suited when imaging test articles with poor emissivity. This technique relies on processing a time-series (typically 30 frames per second) of infrared image data. A Fast Fourier Transform (FFT) is computed at each pixel location. The energy at each pixel location for a fixed frequency is summed across all pixels in the image resulting in a frequency map of the total energy in the image. This frequency map is then used to identify frequencies of interest and a band-pass filter is applied to the original time-series. Finally, the contrast of the band-pass filtered time-series is enhanced resulting in an image set processed both spatially and in time. An example of this process is demonstrated in Figures 5 and 6. Infrared cameras were setup to image a high-aspect ratio aircraft in the NASA Ames UPWT 11-by-11 foot test section. Due to the nature of the wind tunnel model geometry the test article could not be painted with a high-emissivity coating. Typically this is a critical step in performing a successful infrared flow visualization measurement as without such a coating the reflection of the surrounding test section dominate the image. A time-series of infrared images was recorded as the wind tunnel drive increased from zero speed to Mach = 0.5. Figure 7 details three selected images from the frequency map computed from this time-series. The images on the left and right of Figure 7 represent the DC component and the image energy corresponding to 0.061 Hz respectively. These two images show no flow related temperature gradients on the surface of the wing. Like the unprocessed time series data, the dominating features are in fact reflections of the wind tunnel test section. These appear as diagonal lines and are projections of the tunnel slotted walls on the wing surface. The middle image of Figure 7 represents the energy of the aforementioned time-series at 0.017 Hz. This image distinguishes itself from the others in that there are flow features on the surface of the wing. The flow features take the form of wedges, indicating that this narrow frequency range captures a boundary layer transition event as the Reynolds number of the wind tunnel increases. The original time-series is then band-pass filtered to select only the frequency range that contains wedge-like flow features and the contrast is enhanced using the aforementioned techniques. The result is depicted in Figure 8, a boundary layer transition event is now apparent. The number of wedges increase and move forward towards the trip dot line as the Reynolds number increases. This is a typical IR flow visualization result, what makes this novel is the fact that it has been imaged on an unpainted model in a wind tunnel test environment

Figure 7: Three selected frequency map images: DC, 0.017Hz, 0.061Hz (left, middle, right)

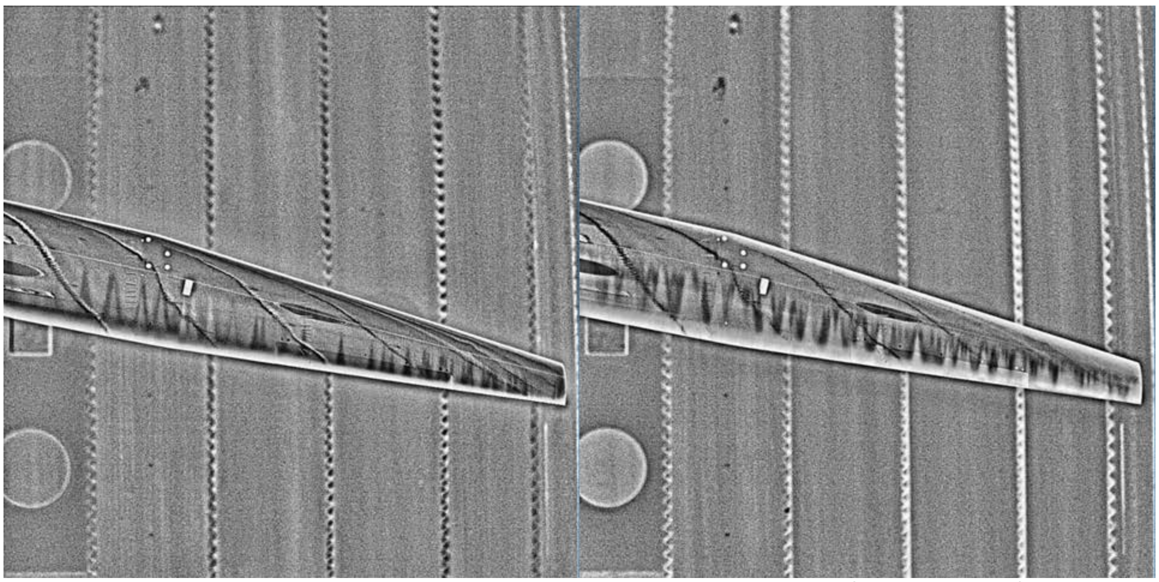

Figure 8: Boundary layer transition on unpainted steel wing-tip: Re/ft = $1.88e^6$, Re/ft = $2.13e^6$ (left, right)