VISUALIZATION AND IMAGE PROCESSING OF AIRCRAFT SHOCK WAVE STRUCTURES

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ABSTRACT

A schlieren imaging system which uses the sun as a light source was developed to obtain direct flow-field images of shock waves of aircraft in flight. This system was used to study how shock waves evolve to form sonic booms. The image quality obtained was limited by several optical and mechanical factors. Converting the photographs to digital images, and applying digital image processing techniques greatly improved the final quality of the images, and more clearly showed the shock structures.

INTRODUCTION

It is crucial for aerodynamicists to examine the shock wave structure on high speed research aircraft to completely understand the detailed physics of the flow field and verify design predictions. Until recently, only wind tunnel flow visualization systems, designed for scale models of the aircraft, could be used to directly examine the shock waves. Data was obtained in flight tests by using chase aircraft to examine the shock structures in the full scale aircraft by probing through the flow field [1]. Using chase aircraft to obtain shock wave data is a slow and expensive procedure, and is limited in how close the chase plane can approach the test aircraft. A direct optical visualization technique to examine flow field images of the shock waves of an aircraft in flight had long been desired.

The density changes across strong shock waves are large enough to make them directly visible by gross refraction of the background under ideal lighting and background conditions, however, ideal conditions are rarely encountered, and the direct visualization obtained this way has a low sensitivity. If the humidity is near saturation, some flow features show up as condensation streaks [2], but this condition is not easily repeated.

The previously used techniques were thus limited, and a sensitive and robust technique was desired to visualize the shock wave flow fields of aircraft in flight. The current paper describes a schlieren system that satisfies the need for sensitive, reliable, and direct visualization of the shock waves of aircraft in flight. Several problems were encountered in early versions of this visualization system, which resulted in flawed images. Image processing techniques are described which were developed to give better final images.

OPTICAL SYSTEM DESCRIPTION

The schlieren for aircraft in flight (SAF) combines a high resolution telescope with focusing schlieren features [3] and a streak camera. The setup used is shown in Figure 1. The telescope tracks the sun so that the suns image is stationary at the focus. A mask with a narrow curved slit is positioned to block all but a thin line at the edge of the sun, and a small region of sky next to the edge. An aircraft is flown through a field of view crossing this edge, and the aircraft image is sharply focused on the film plane. The film strip moves to follow the aircraft motion. Density gradients around the plane refract the light, causing brightness variations along the light line as the film is moved past it, resulting in a schlieren image of the flow field.

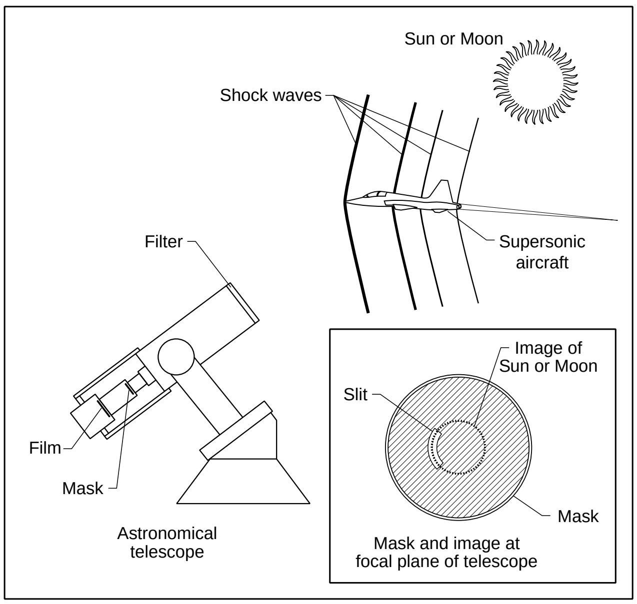

FIGURE 1. SETUP OF SCHLIEREN FOR AIRCRAFT IN FLIGHT

Resolution of an image obtained at a large distance through the atmosphere is limited by atmospheric turbulence. During a hot day, this limit can be quite restrictive, but generally resolution of about 10 to 20 µrad can be obtained if the viewing angle is not too low. Focus errors and inadequate optics can also limit the image quality. The close proximity of the focal plane of the aircraft to that of the light source (the edge of the sun), and the need to keep the slit very narrow (to get good sensitivity) also have the potential to degrade the image.

The telescope used for the initial test was a 200 mm aperture Schmidt-Cassegrain telescope with a 1.9 m focal length. 16 mm Kodak XX film was used to record the image. A neutral filter was used to cut the sun intensity to a suitable level. The optical system to this point was capable of resolution better than 5 µrad under ideal conditions. Due to the film transport design, the primary focal image located at the cutoff mask had to be relayed to a second focus at the film location.

The relay optics did a good job on-axis, but degraded the image noticeably at moderate distances off-axis. Since the initial setup was only intended to demonstrate the validity of the technique, this problem was not corrected for the preliminary test.

PRELIMINARY TEST AT NASA WALLOPS FLIGHT FACILITY

The initial flight test to demonstrate the new system was conducted from Wallops Flight Facility. Supersonic flights at this facility had to be made at least 8 km off shore to avoid sonic booms in populated areas.

The SAF system was first tested using a T-38 aircraft flown from NASA Langley Research Center to the Wallops test area. The supersonic pass was flown off Assateague island (close to Wallops) at an altitude of 4 km and a slant range of 10 km from the camera. The plane flew at M=1.1, and was guided by the Wallops Instrument Landing System (ILS). The photo shown in Figure 2 is the first SAF photo obtained with an aircraft in the image.

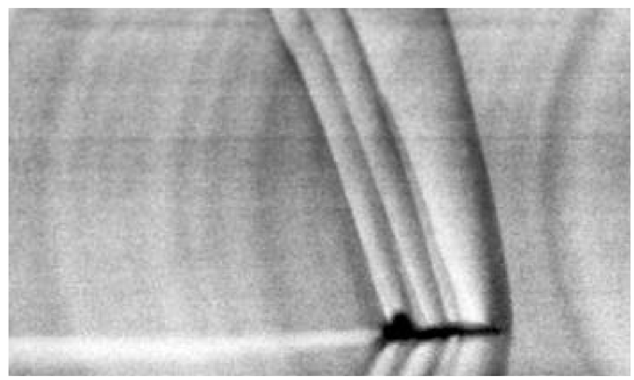

FIGURE 2. T-38 AT M=1.1 AND 10 km RANGE

The combination of atmospheric turbulence with limitations in the optics, film graininess, wind induced vibration of the telescope and slight variations in the film speed resulted in a resolution limited to about 20 to 40 µrad in the image, which was significantly less than the optimum for this system. The wind induced vibration and variations in film speed resulted in curved bands (corresponding to the edge of the sun) with noticeable brightness variations appearing in the photograph. Slight irregularities in the masking slit edge resulted in streaks running in the direction of film motion. Scratches caused by trapped sand grains were also a slight problem. Additionally, the aircraft was near the edge of the photo, and is thus not as sharp as features nearer the middle of the image.

About one plane length above the plane, the 6 shocks are shown to merge to 4 shocks. The image did provide a satisfactory proof-of-concept for the new technique, but clearly indicated the need to improve the system.

SONIC BOOM TESTS AT NASA DRYDEN FLIGHT RESEARCH CENTER

Successful demonstration of SAF as a tool to examine the flow field of aircraft in flight led to the incorporation of the technique into the sonic boom program at NASA Langley. The next step was to evaluate the use of SAF to examine both near and far field shock waves to determine the changing structure of the shock waves as they propagated to the ground. Several different aircraft were used in the sonic boom study including the F-18 and SR-71. The planes were flown at NASA Dryden Flight Research Center, which had supersonic test areas over land.

Modifications were made to try to overcome some of the problems encountered on the original optical system to try to obtain better images. The features considered most objectionable for the initial system were lack of uniform sharpness, film graininess, and banding. A better optical relay was installed, and a finer grain film was used. The film selected, Eastman 7302, also had higher contrast than XX, so would show the weaker shocks encountered at higher altitudes better. An attempt was also made to make the film run smoother, but this did not work well, as will be discussed later.

Since the evolution of the shock wave structure from the aircraft was the primary objective of the SAF portion of this program, the aircraft location did not have to be as accurately controlled in real time as when just the flow field around the aircraft was the primary objective. For these flights, inertial navigation systems (INS) were used to position the aircraft. This was far less accurate than the Wallops ILS positioning system, but was adequate for the SAF portion of the sonic boom tests.

The first aircraft flown with the modified system was an F-18. While the aircraft image was not highest priority for this test, most passes were made to image the shock field close to the aircraft. The plane was flown at Mach 1.4, at an altitude of 10.7 km and a slant range of 18.3 km. The photograph shown in Figure 3, shows the only image obtained during this test where the aircraft image was in the field of view.

FIGURE 3. F-18 AT M=1.4 AND 18.3 km RANGE

Unfortunately, the image was considerably out of focus, and also showed extremely bad brightness banding. The modification to smooth the film motion obviously did not work well in some of the images, and this image had one of the most severe brightness variations. Also, the higher contrast film exaggerated the banding more than the previous film. The image quality was improved considerably by digital image processing which will be discussed in the next section.

The main tests in the sonic boom program were made with an SR-71. This aircraft came closer to the size and configuration of a potential SST than other aircraft available at Dryden. The SR-71 was flown at different mach numbers and altitudes to study the sonic booms. The photographs of the SR-71 were made at different distances from the aircraft to examine how the shock structure varied. The image shown in Figure 4 was made at Mach 1.25, with the plane at 11.6 km altitude, and at a slant distance of 19.5 km. The plane is moving to the right for this photo.

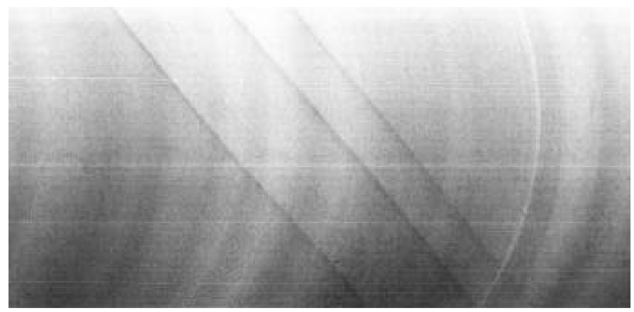

FIGURE 4. SHOCK WAVES 300 m ABOVE SR-71 AT M=1.25 AND 19.5 km RANGE

The image, which was made about 300 m above the aircraft, shows three shocks clearly. The image was fairly sharply focused, so the shock waves are much sharper than the F-18 shocks of Figure 3. Low contrast detail, non-uniform exposure, scratches, and some banding limit the image quality. The resolution was estimated to be better than 20 µrad for this case and was probably most limited by atmospheric turbulence.

In order to determine how weak a shock wave could be imaged in the SAF system, images were made at different distances below the SR-71. The largest distance examined was 3.7 km below the aircraft, and the shock image for that case is shown in Figure 5. The aircraft for that image was at 11.6 km altitude and 19.5 km slant range, with the plane traveling at Mach 1.4. Again, the plane is moving to the right in the photo.

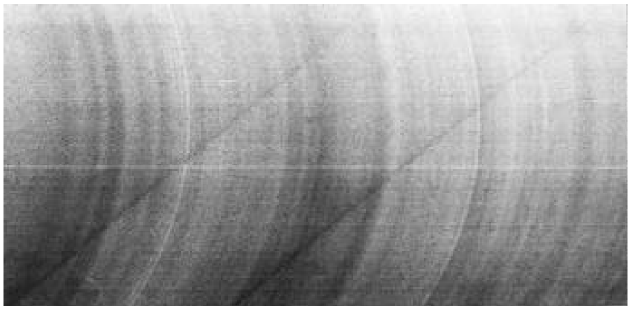

FIGURE 5. SHOCK WAVES 3.7 km BELOW SR-71 AT M=1.4 AND 19.5 km RANGE

Obtaining a useful image of the shock at such a large distance below the aircraft demonstrated that the SAF system was usable over much of the shock path to the ground. The image was sharply focused, but was low contrast, and also had some scratches, non-uniformity of exposure, and banding problems. It was clear that considerable enhancement was desirable to improve the images.

The next section describes how the images were enhanced to show the flow field more clearly.

DIGITAL IMAGE PROCESSING

The goal of the digital image processing is to correct for the image flaws introduced by the imaging system and to enhance the appearance of the shocks. The main image degradation features were banding, non-uniform exposure, scratches, streaks, and low contrast detail. The F-18 image had the most severe degradation, so is used as an example to illustrate the processing steps.

The film from the F-18 flight was scanned to produce a digital image consisting of 352 rows by 472 columns of pixels with gray level values ranging from 0 to 255, and is shown in Figure 3. The curved banding pattern that appears in the image was due to a combination of wind induced vibration and unsteady film speed. Several dark horizontal bands are also visible, caused by slight flaws in the mask, and some scratches. Removal of both type of bands is accomplished using frequency domain filtering.

Frequency Domain Filtering

The process of frequency domain filtering involves computing the Fourier transform of the image to be filtered, multiplying the result by a filter function, and taking the inverse transform to produce the filtered image.

To simplify the task of specifying a high performance filter function, the curved bands were converted to straight vertical bands by shifting each row of the original image by an amount corresponding to the curvature of the bands. The result is shown in Figure 6. Prior to the row shifting , the image was padded on both sides by replicating the left and right most columns.

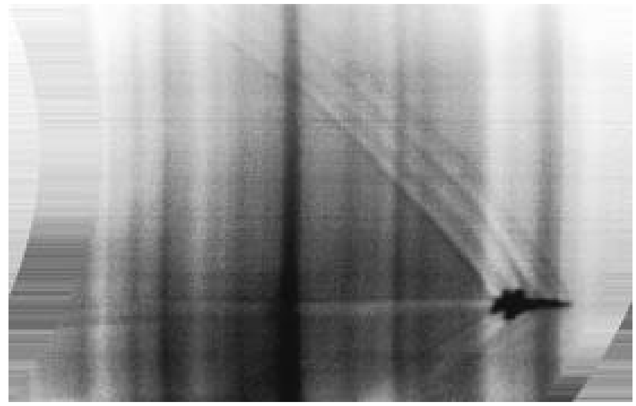

FIGURE 6. ROW SHIFTED IMAGE

The Fourier spectrum of the shifted image is shown in Figure 7. The vertical bands produce concentrated energy in the horizontal axis of the Fourier spectrum. The dark horizontal bands evident in the spatial domain are responsible for the concentrated energy in the vertical axis of the Fourier spectrum. The average vertical brightness gradient in the spatial image, which resulted in non-uniform exposure, also was seen in the vertical axis of the Fourier spectrum, but near the middle (since it was a low spatial frequency).

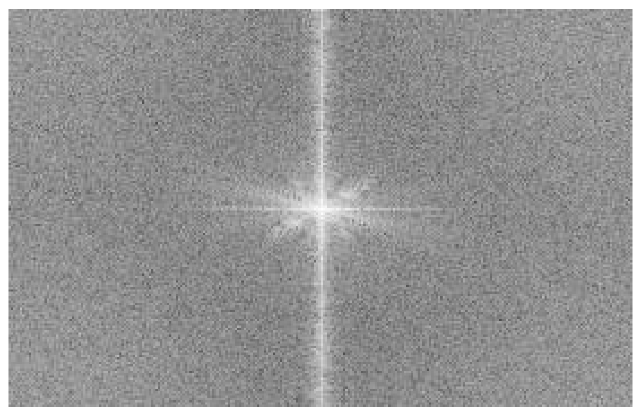

FIGURE 7. FOURIER SPECTRUM

The filter function used is shown in Figure 8. The thick horizontal and thin vertical lines completely attenuate the horizontal and vertical frequencies in the Fourier spectrum, while passing, without attenuation, all other frequencies. The thickness of the lines was determined by trial and error so as to give the best looking final result.

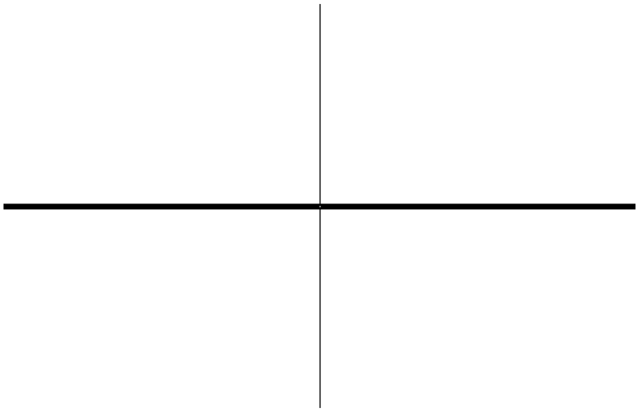

FIGURE 8. FILTER FUNCTION

The result of frequency domain filtering is shown below

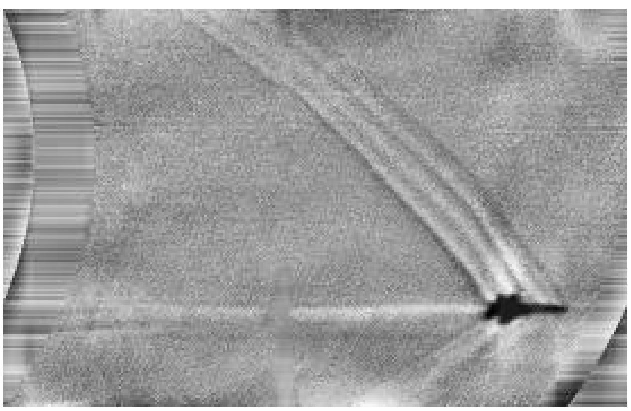

FIGURE 9. FILTERED IMAGE

Each row in the filtered image is shifted back to its original position in Figure 10.

FIGURE 10. ROW SHIFTED FILTERED IMAGE

Further Image Enhancement

To further enhance the appearance of the shocks, the filtered image is processed using unsharp masking and contrast stretching. The general process is to subtract a blurred version of the input image from the unblurred image (highpass filtering) and add part of the unblurred image back in to produce a resulting image that appears more like the input image, but with a degree of edge enhancement and overall contrast reduction. The blurred image is created using a boxcar average, or spatial convolution with a kernel of all 1's. Prior to blurring the image, the dark pixel values corresponding to the aircraft are replaced with a background average value to preserve the detail closest to the aircraft. The unsharp masking has two input parameters: the blurring kernel size, and the scalar value specifying the portion of image to add back to the highpass filtered image. The choice of both parameters is highly subjective and requires some experimentation to achieve the desired result. A blurring kernel size of 31 and a scalar value of 25 for the percentage of the input image to add back in was found to do the best job of enhancing the shock features in the image while at the same time maintaining as much of the original appearance of the image as possible. Figure 11 shows the unsharp masking result scaled to a range of gray levels between 0 and 255.

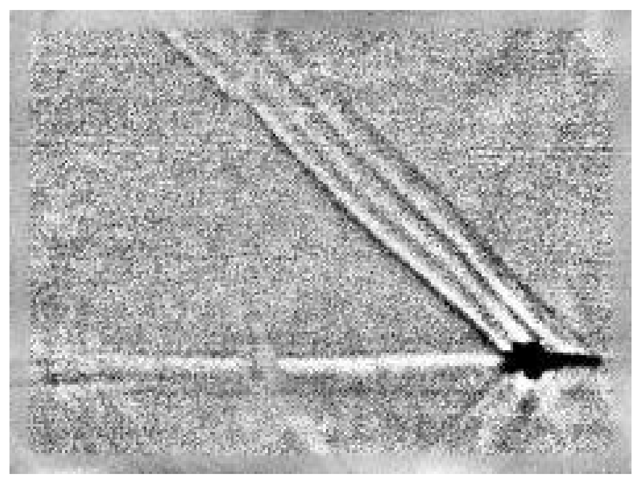

FIGURE 11. FINAL ENHANCED IMAGE OF F-18 FROM FIGURE 3

Enhanced Remaining Images

The enhancement process was applied to the other images previously shown. In addition, most of the scratches were edited out. To clean up the scratches in the images, a sobel operator was used to define regions in the image that were scratches. The thresholded sobel image was treated as a mask of sorts. Values for each pixel in the original image underlining the areas of the mask image were replaced by the minimum value in a 5x5 neighborhood of the original pixel. The minimum values were used because the scratches were much brighter than the background values. Completely enhanced images are shown in Figures 12-14.

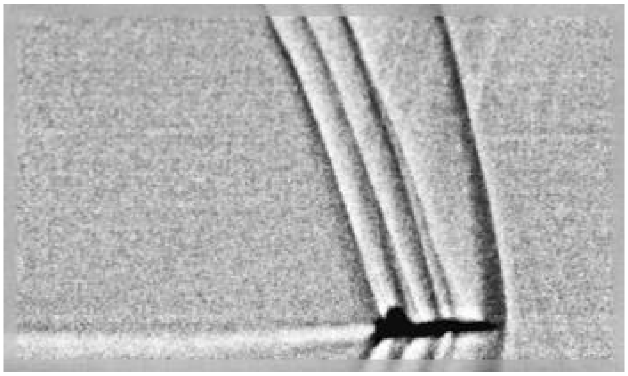

FIGURE 12. ENHANCED IMAGE OF T-38 FROM FIGURE 2

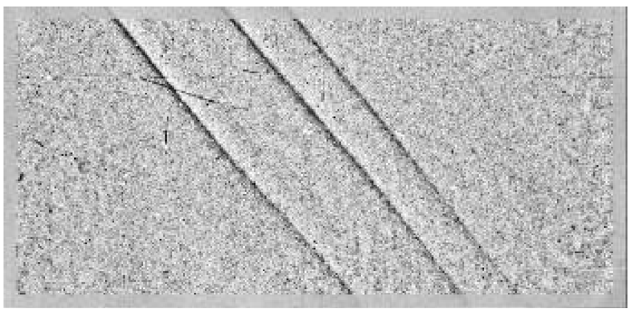

FIGURE 13. ENHANCED IMAGE OF SR-71 SHOCK WAVES FROM FIGURE 4

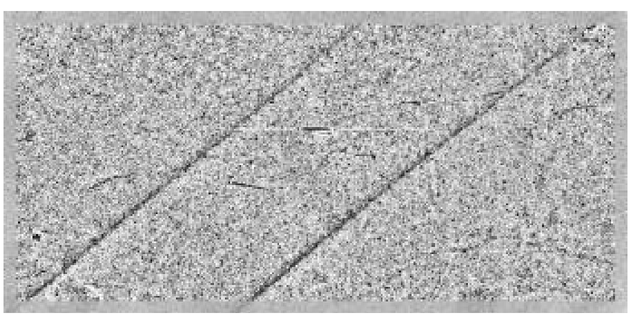

FIGURE 14. ENHANCED IMAGE OF SR-71 SHOCK WAVES FROM FIGURE 5

In every case, the enhanced images are much better than the original images. In Figure 13, the enhanced shock image from the SR-71 appears to show a couple of additional weak shocks not seen in the unenhanced image. For those images that were sufficiently poor to start with, the limited information (signal to noise ratio and resolution limit) placed significant limits on improvements. The result of such a limitation shows up in Figure 11. The enhanced image shows the shock structure far better than the original image, and the banding is removed, but significant background noise also shows up. The other images also show some background noise, but less than in Figure 11.

CONCLUDING REMARKS AND FUTURE PLANS

A flow visualization technique has been developed which obtains the flow-fields of high speed aircraft. The first operational version of this technique used a special streak camera to obtain images. A combination of film transport speed variation and wind induced vibration resulted in significant brightness variations (banding) which degraded the image quality. Film graininess, scratches, and lack of sharp focus also limited the quality of some images. The photographs were converted to digital images, and several digital image processing techniques were used to improve the image quality. Significant improvements were made in all of the photos, and final images more clearly show the shock structures.

Improved versions of the schlieren imaging system are currently under development, including a version using an electronic Time Delay and Integration camera to replace the moving film strip, which should greatly reduce the banding problem. An air -to-air system is also being built to obtain high resolution images of aircraft at high altitudes. These new systems should allow better original images to be obtained. The electronic camera images are recorded directly in digital form, so enhancing them would be particularly easy. We expect far better flow visualization images of aircraft shock wave structures to be obtained with the new systems than the images presented in the current paper.

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