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ANALYSIS METHODS FOR VESSEL GENERATED SPRAY

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ABSTRACT

The droplet sizes and velocities contained in vessel generated spray are difficult to quantify. This paper describes three different methods to quantify velocity and size distributions from high speed video of spray from a planing boat. These methods include feature tracking, displacement tracking and video inversion.

For the feature tracking method, the images were pre-processed using contrast limited adaptive histogram equalization, and then converted to binary images with a specific intensity cutoff level. Image statistics were then generated from this image, including droplet area and effective diameter. These images were processed using commercial PIV software to obtain velocities. For the displacement tracking method, the images were also converted to binary images with a specific intensity cutoff level. Image statistics were again compiled from this binary image. A droplet filter was then applied using a binary erosion image processing technique, where large droplets were removed because the entire droplet may not be in frame, and small droplets were removed because they might not overlap between frames. Droplets were then tracked by comparing the bounding boxes of two droplets between time frames. The video inversion method consisted of the manipulating the original high speed videos from spatial x-y frames in time space to time-y frames in x-space, where the x-axis is longitudinally along the ship and the y axis is vertical to the ship. From this orientation, the speed of the general spray mass could be determined by summing the pixels in time columns for each x frame.

Comparisons of droplet size distribution between the feature and displacement tracking method yield qualitatively similar results, with some disagreement likely due to the different threshold levels. The trend of the distribution curve suggests that both methods are unable to resolve the smallest droplet sizes, due to the processing filters applied as well as the field of view of the camera. The three analysis methods compare well in their spray velocity computation, and are also similar to spray speed predictions found in the literature for a given geometry and vessel speed.

INTRODUCTION

Images of spray generated by a high speed planing vessel were collected using a high speed video collection system. An example image is shown in Figure 1. The images were collected at a rate of about 2000 frames per second, with a width of field of view of approximately 20 inches. This width corresponds to approximately 0.2 inches per pixel.

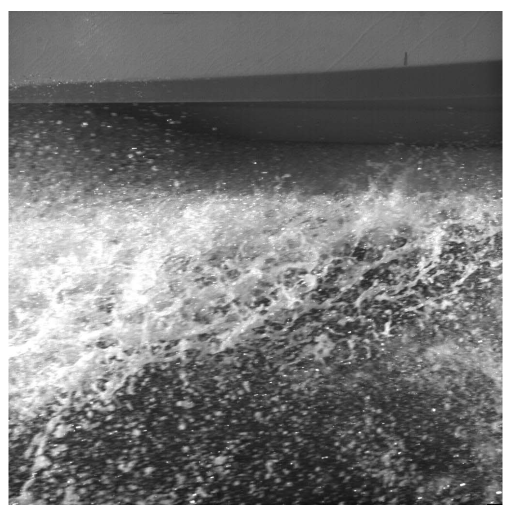


Figure 1. Example image from high speed video.

Predicting the magnitude and direction of spray velocity is not necessarily a straightforward process. Experimental observations (Savitsky, 1964, 2007) have shown that the space angle between the spray velocity and the stagnation line on a planing vessel can be taken as equal to the space angle of the incoming free stream velocity relative to the stagnation line. This concept is similar to the "principle of reflection" in classical physics as applied. Through the application of this method, spray magnitude and direction can be determined based on vessel speed and geometry. Table 1 shows the calculated spray velocity based on estimated trim and deadrise angle for the planing boat conditions that were captured, where U is the velocity along the longitudinal axis of the hull, V is the velocity along the vertical axis of the hull, and W is outboard from the centerline.

Table 1. Calculated velocity based on estimated trim and deadrise angle.

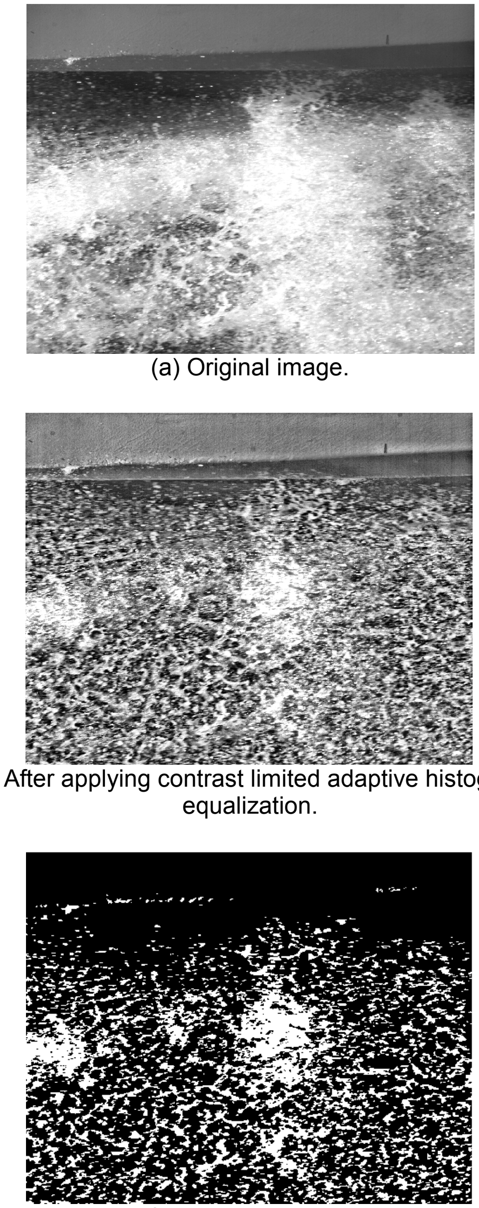
Ship Speed	Trim Angle	Deadrise Angle	U	V	W
kts (ft/s)	deg	deg	ft/s	ft/s	ft/s
30 (50.6)	10	40*	43.4	19.1	11.5
30 (50.6)	10	37**	41.2	22.7	15.5
40 (67.5)	10	40*	57.8	25.5	15.3
40 (67.5)	10	37**	55	30.3	20.6

*~11' aft of stem
**~12.58' aft of stem

DATA ANALYSIS

Three analysis methods were utilized to analyze the spray images collected, which include a feature tracking method, a displacement tracking method, and a video inversion method. For the feature tracking method, the relative contrast of the original images was modified using a contrast limited adaptive histogram equalization, and then converted to binary images with a specific intensity cutoff level (Figure 2). After the binary conversion, droplets with an area of less than 4 pixels are removed, and the image is median filtered using a 3x3 pixel window to reduce the noise. Image statistics were then compiled from the final image, including droplet area, eccentricity, effective diameter, centroid, and perimeter (Figure 3).

The binary images were further processed using commercial PIV software to obtain velocities. In using this software, a type of pattern matching is used to track droplets from frame to frame. Only droplets of an area greater than 16 pixels are retained (Figure 4a). The velocity results are returned on a regular grid with a 16 pixel spacing (Figure 4b). Any vectors which deviate mode than 45^{o} from centerline are removed. Velocity vectors are then interpolated to the droplet centroid weighted by the droplet intensity using cubic spline interpolation (Figure 4c).



(a) Original image.

(b) After applying contrast limited adaptive histogram equalization.

(c) After thresholding filtered image to binary image with cutoff at 0.7.

Figure 2. Steps of preparing images for feature tracking method (a-c).

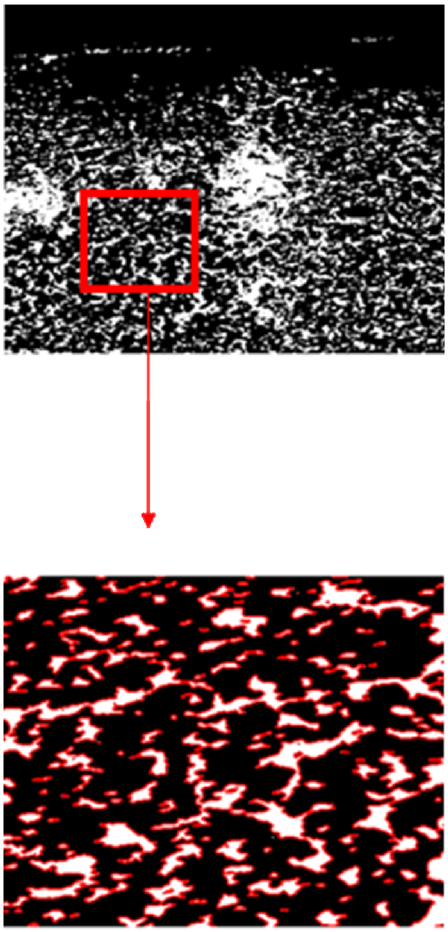
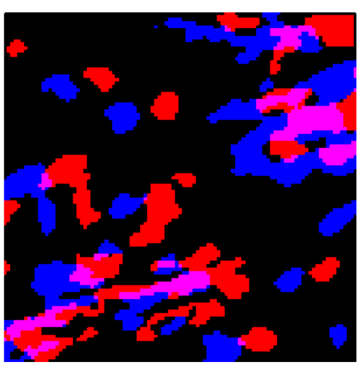
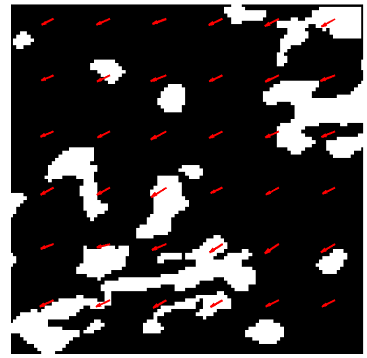


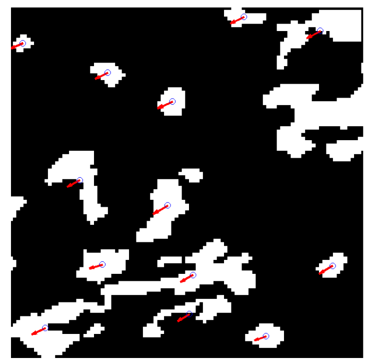
Figure 3. Sample image from which droplet perimeter statistics were computed for the feature tracking method.



(a) Overlay of image pair, with first image shown in red and second as blue.



(b) Computed velocities on regularly spaced grid.

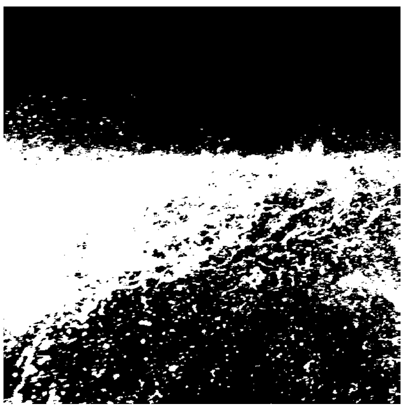


(c) Velocitied interpolated to droplet centroids.

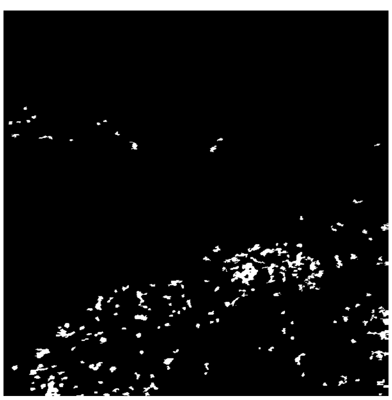
Figure 4. Steps in PIV analysis for feature tracking method.

For the displacement tracking method, a mask is applied to the non-spray areas (ship) and is then converted to a binary image with an appropriate threshold level (Figure 5b). Once the binary image was made, an image processing library from commercial software was used to computer droplet statistics as before. A droplet filter was then applied to the binary image using binary erosion image processing technique; large droplets were removed (less than 8 erosions) because the entire droplet might not be in the frame, and small droplets were removed (greater than 2 erosions) because they might not overlap between frames (Figure 5c). Droplets were then tracked by comparing the bounding boxes of two droplets from consecutive frames. If the bounding boxes overlapped in the direction of the flow then they were considered the same droplet. Velocity vectors were computed using the difference in centroid locations of droplets between consecutive frames. Outliers were removed by assuming that the droplet velocity vector should not deviate by more than 20 degrees from the previous frame.

(a) Original image.



(b) Image after applying mask and converting to binary.



(c) Final binary image after applying droplet filter.

Figure 5. Analysis steps for displacement tracking method.

The third method used was the video inversion method. In this method, images were stacked in time to form a cube of data in (x,z,time) coordinates (Figure 6). This data cube was then inverted into (z,time,x) coordinates (Figure 7). Frames from the x coordinate nearest the bow and the stern are shown in Figure 8 and Figure 9, respectively. The next step was to sum the pixels columnwise to get one value for each column, which measures the spray “clouds” passing through, which generated one line per frame (Figure 10). Cross-correlation was then performed between subsequent frames to determine the time shift of position. The time shift versus x-position was then plotted to determine velocity in direction of ship motion (Figure 11).

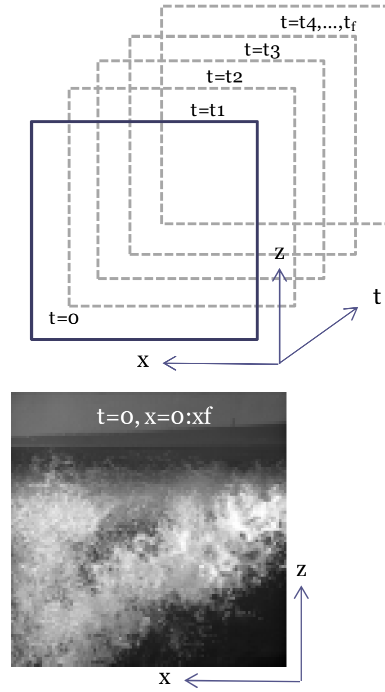


Figure 6. Original data cube for video inversion method.

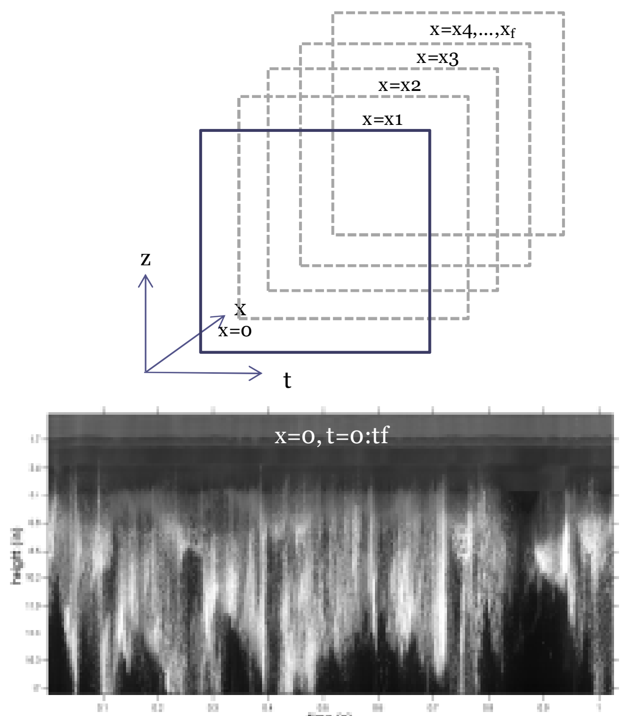


Figure 7. Inverted data cube for video inversion method.

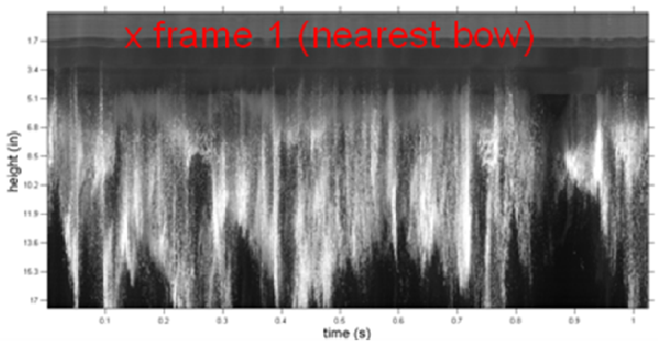


Figure 8. Inverted data frame for x frame 1 (location nearest the bow).

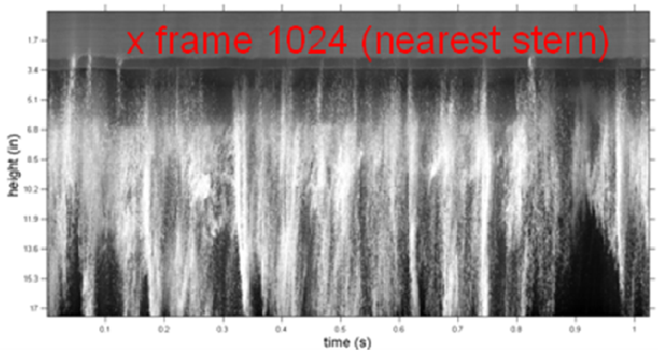


Figure 9. Inverted data frame for x frame 1024 (location nearest the stern).

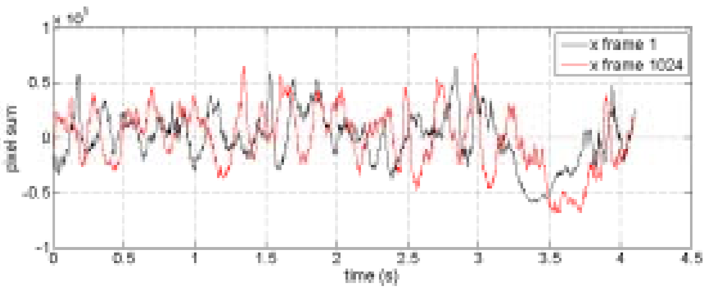


Figure 10. Pixel sums for first and final x frames from Figure 8 and Figure 9.

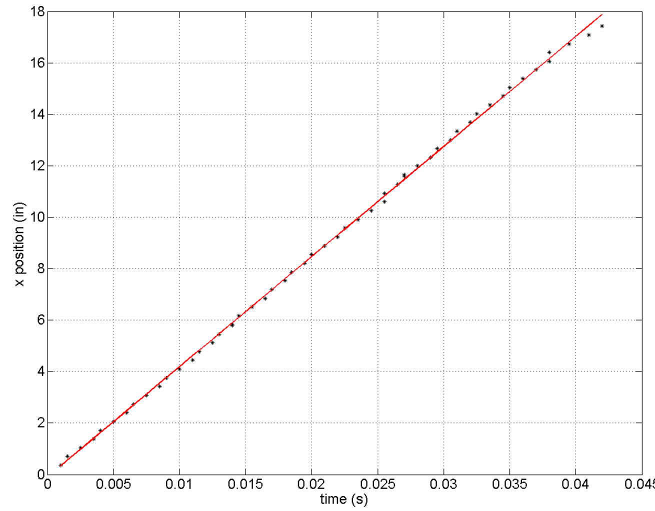


Figure 11. Time shift of pixel sums between frames versus x position to find spray velocity in direction of ship motion.

RESULTS

The droplet size distribution from the feature tracking method and the displacement tracking method are shown in Figure 12. The distributions were computed from all droplets found over a single run of length of about 1s. The sharp cutoff for the feature tracking method corresponds to the 4 pixel filter applied. This plot show that the peak of the distribution may be at an area that is too small to resolve from this particular camera setup. Computations of the droplet size distribution using two different methods yield qualitatively similar results; differences in the distribution between the two methods are likely due to different thresholding levels.

Figure 13 shows the calculated velocities for each of the three methods, plus the range of values using the predictions described in the Introduction section. Overall, the computed velocities are similar across analysis methods, and also similar to the predicted range. The disagreement between the predicted and computed vertical velocity is likely due to greater error in the calibration of the vertical extents of the field of view.

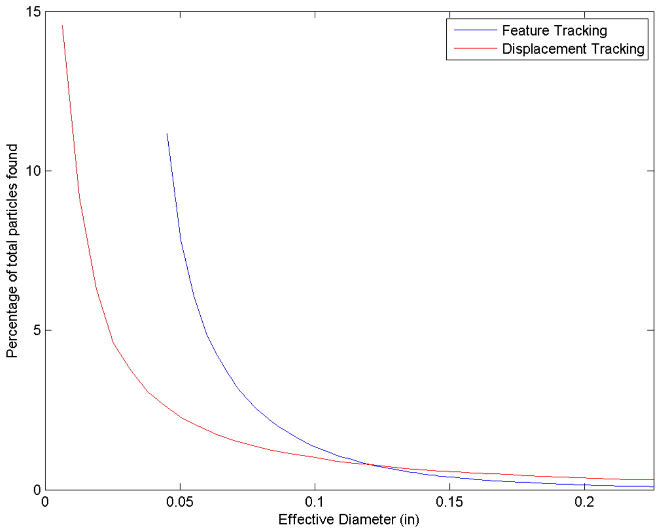


Figure 12. Comparison of droplet size for ship speed of 30 knots (50 ft/s).

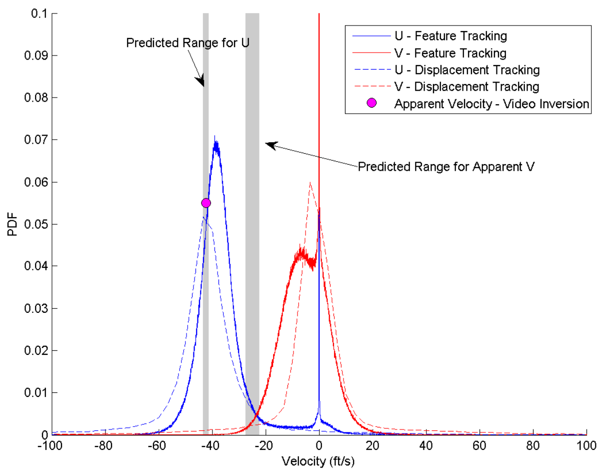


Figure 13. Comparison of velocity calculations between the three methods and the prediction.

CONCLUSIONS

Computations of size distribution compare fairly well between the feature tracking and displacement tracking methods. Sharp cutoffs at the lower end exist due to filtering methods and image resolution limitations. As a result, the peak of the distribution may be at an area that is too small to resolve from this particular camera setup.

Velocity results from the three analysis methods described in this paper compare well, and these results compare well with the predictions. While the video inversion method only generates a single velocity for each run, both the feature tracking and displacement tracking methods generate a velocity distribution for each run.

ACKNOWLEDGMENTS

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