1. LIC for Surface Flow Feature Detection

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ABSTRACT

The Line Integral Convolution (LIC) algorithm has received a lot of attention and interest. Yet, only a few of the current LIC related algorithms deal specifically with color textures for automatic detection of flow features. In this paper, I give a brief review of current work in this area.

1.1 Problem

In windtunnel experiments, scientists are interested in studying the flow behavior during actual flow conditions. A common technique is to inject smoke during the experiment and to analyze the flow behavior by observing the flow pattern formed by the smoke. Some scientists have analyzed the flow pattern near the surface of the test model by coating the body with a mixture of paint and oil and then examining the flow pattern generated by the paint/oil. The resulting flow pattern is commonly referred to as *surface oil flow*.

In numerical flow visualization, vector plots and streamlines have been used to simulate surface oil flows. These techniques have provided useful insights about the surface flow. Unfortunately, these techniques require the users to know a priori locations to compute the particles and vectors. Another disadvantage is that the resulting flow patterns are discrete, and the output image quality may be cluttered with dense vectors/streamlines. The LIC algorithm generates surface flow patterns that are very intuitive to understand and it does not have the disadvantages of the conventional vector plots and streamlines.

Good progress has been made with the LIC algorithm introduced by Cabral and Leedom [1.1] which produces synthetic texture patterns based on an input vector field. An excellent tutorial on LIC can be found in the course notes by Ma et al. [1.2]. Because the LIC technique generates texture patterns that reveal the flow direction in the given grid domain, it is ideal for simulating surface oil flows in CFD applications. Although the algorithm has been shown to be very effective in revealing global flow features, the monochrome LIC images generated by the algorithm sometimes do not reveal flow features clearly because these features are displayed on a gray-scale texture background. Figure 1.1 depicts an image of surface flow computed

using the LIC algorithm on a cylindrical body. The monochrome texture depicts interesting flow separation and reattachment lines along the cylindrical body. There are also several critical points, where the velocity is zero, near the nose of the cylindrical body. However, some of these critical points are not easily seen because of the monochrome texture background. Scientists would like to see these interesting features automatically highlighted along with the flow texture patterns.

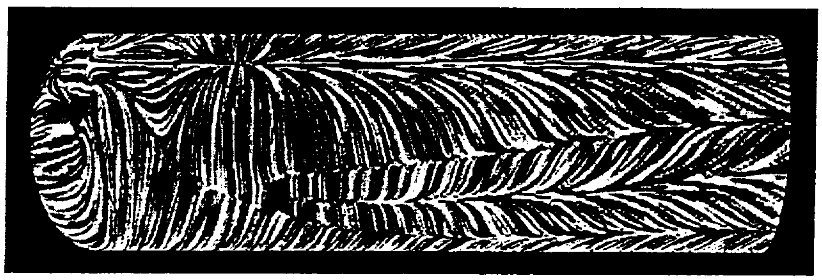

Fig. 1.1. Monochrome surface flow texture near the surface of a cylindrical body.

1.2 Scalar Function

A straightforward way to enhance flow textures is to color the texture by a selected scalar function. Some common functions are pressure coefficient, velocity magnitude, and vorticity magnitude. A particular scalar function may or may not highlight the flow features. Furthermore, the color map used may not correlate well with the underlying flow texture patterns. For example, the color texture may not clearly delineate flow separations and reattachments. The top of Figure 1.2 depicts surface flow colored by pressure coefficient. The input flow field is the same as the one used for Figure 1.1. Note that this scalar function highlights the critical point near the top of the cylindrical body but not those near the nose of the cylinderical body. Shown in the lower half of Figure 1.2 is the flow texture colored by velocity magnitude. For this data set, the velocity magnitude function gives a very good depiction of the separation and reattachment lines and several critical points.

Figure 1.3 shows another comparison of a monochrome texture with scalar colored texture using a delta wing flow data set. The monochrome texture (upper left) does not give a clear depiction of the interesting flow separations and reattachments along the leading edge of the delta wing. The pressure coefficient texture (upper right) does not reveal the flow features along the leading edge of the wing. The velocity magnitude texture (lower left) gives

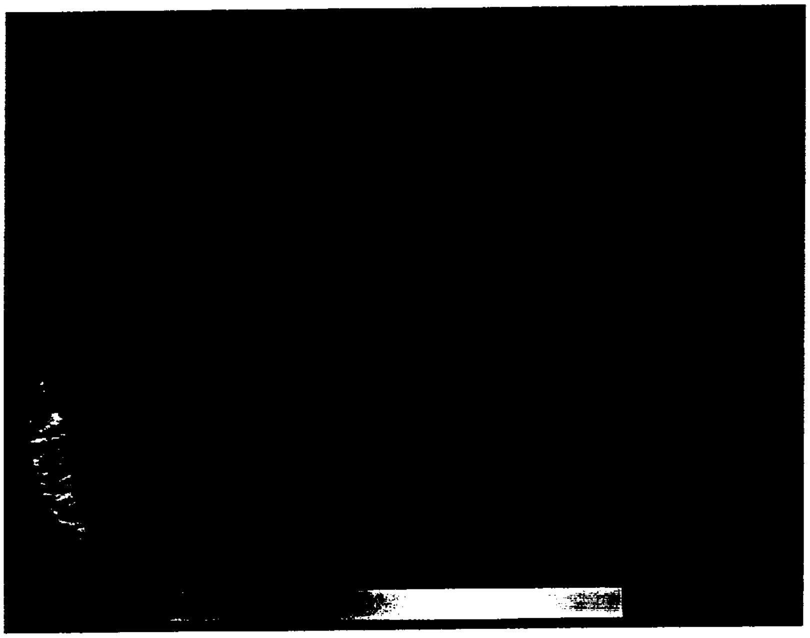

Fig. 1.2. Color surface flow texture based on pressure coefficient (top) and velocity magnitude (bottom). Lowest value is colored in blue and highest value is colored in red.

some correlation of the critical points (dark blue regions) and the flow separations and reattachments along the wing. However, due to the color map used, there are some misleading red streams near the nose tip of the wing even though the flow is quite steady in that region. Shown in the lower right of Figure 1.3 is the texture colored by vorticity magnitude. This scalar function seems to give the best correlation of flow features with color.

1.3 Velocity Direction

Another common method is to color the texture based on velocity direction. In a case study, Johannsen and Moorhead [1.3] used colors to represent flow directions in their study of ocean basin flow features. Using the HSV color model, they mapped the vector length to saturation and lightness. Boring and Pang [1.4] have also investigated mapping of velocity direction and magnitude to HSV value and hue. In their application, they used light sources to select and highlight flow regions with similar flow directions. We have found that the velocity direction is best represented using color when visualizing flow separation and reattachments [1.5]. Figure 1.4 shows surface flow colored by velocity direction. The lower half depicts a counterclock-wise circular flow colored by velocity direction. From the figure, it shows that horizontal velocity

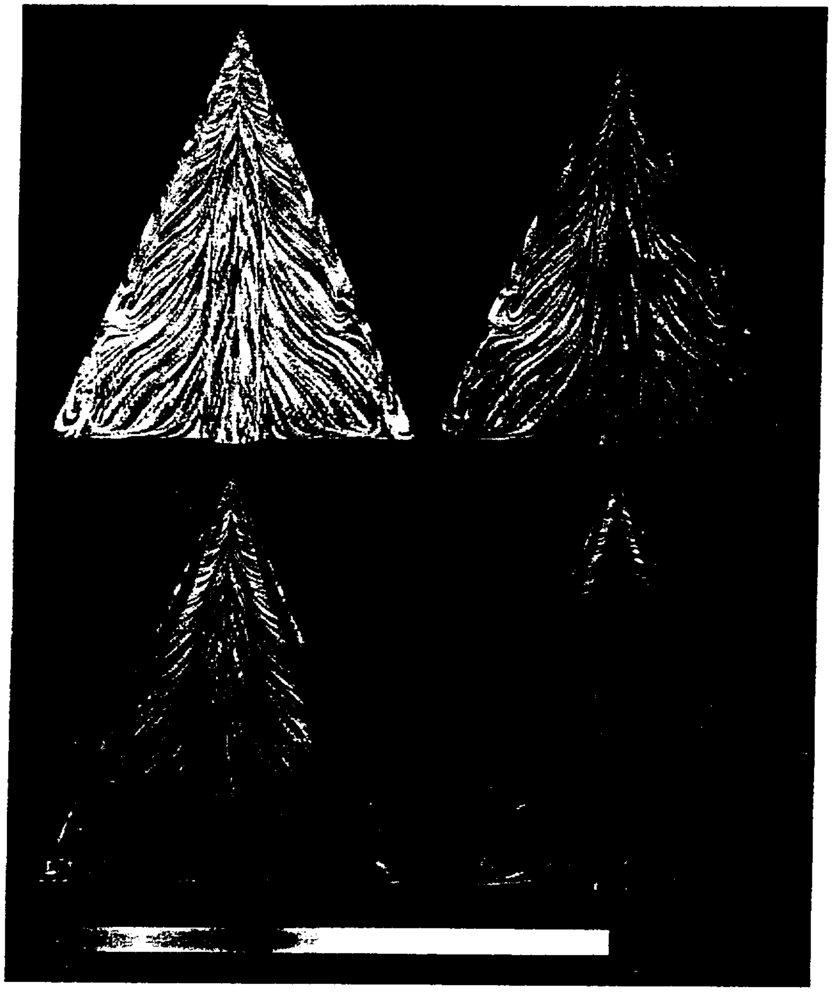

Fig. 1.3. Delta wing with flow texture colored by monochrome flow lines, pressure coefficient, vorticity magnitude, and velocity magnitude (clockwise).

direction is colored in red or blue depending on the flow direction. Note the sharp delineation of the separation and reattachment lines shown on the hemispherical cylinder body. The critical points near the nose of the cylinder are also depicted clearly.

1.4 Flow Separation and Reattachment

Color texture is useful for depicting global information over the entire grid surface. Sometimes, however, the color may be more visually dominating

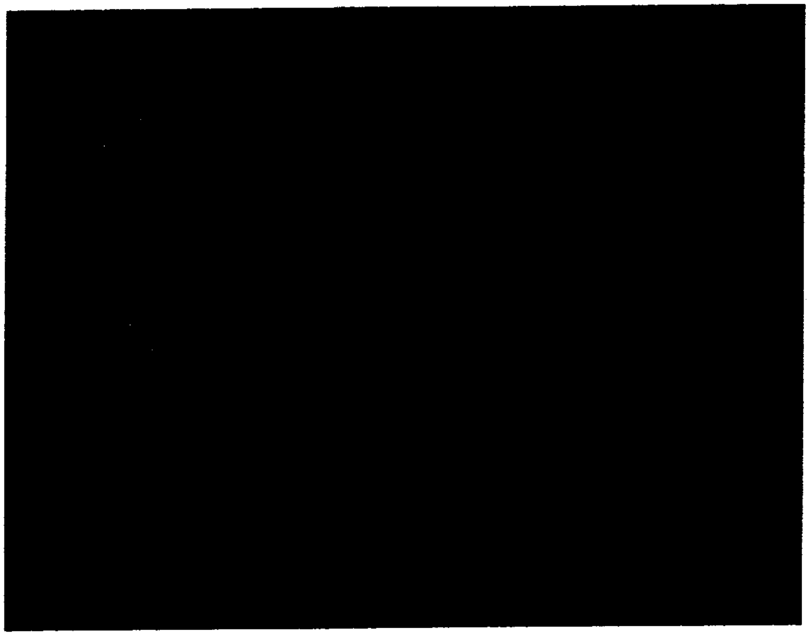

Fig. 1.4. LIC texture colored by velocity direction.

than the flow texture pattern. This is fine as long as the color change always highlights the flow features. But it is not guaranteed. One simple and fast solution is to color the texture only when the neighboring velocity changes significantly in direction and to keep the texture monochrome everywhere else. In flow separation, streamlines converge and then deflect from the surface of the body. This implies that the streamlines converge along the separation line from opposite directions. Analogously, when the flow is impinging on the surface, streamlines diverge along a reattachment line. By computing the angles formed by neighboring velocity vectors, we can check for the angles that are greater than some threshold value [1.5]. We then color the textures that meet this criterion. The algorithm proceeds as follows: At each texel $t(i,j)$, an average velocity vector $v_a(i,j)$ is computed based on the average of the velocity vector at $t(i,j)$ and its eight neighboring texels. Then, the velocity angle $v_{ang}(i,j)$ at $t(i,j)$ is set to the maximum of the dot products of $v_a(i,j)$ and the average velocity vectors from its neighboring texels. Let $v_{ang}(i,j) = max(v_a(i,j) \bullet v_a(k,l))$, where $k = i-1, i+1$ and $l = j-1, j+1$. The velocity angle $v_{ang}(i,j)$ is then mapped to a color value. Hence, by selecting texels with velocity angles exceeding a threshold, one will only color textures where the flow direction changes rapidly. Shown in the upper half of Figure 1.5 is the LIC texture colored by velocity angle. Note that the color highlights the regions where flow separation and reattachment occur.

Using the velocity angle algorithm described above, flow separation and reattachment lines are both colored in the same color. It is possible to automatically distinguish between these two cases. Flow separations occur when the flow is leaving the surface; and when the flow is impinging on the surface, it creates flow attachments. Hence, by examining the velocity component normal to the grid surface, we can attempt to classify separation and reattachment [1.5]. In the lower half of 1.5, separation regions are colored in green, and the reattachment regions are colored in dark red.

Flow separation and reattachment lines are even more easily distinguished by using the two techniques in this section than when they are colored by a scalar function. Figure 1.6 compares the three techniques: colored by velocity direction, velocity angle, and separation and reattachment line classification using a delta wing data set. The separation and reattachment line classification technique gives an immediate visual impression of the flow features.

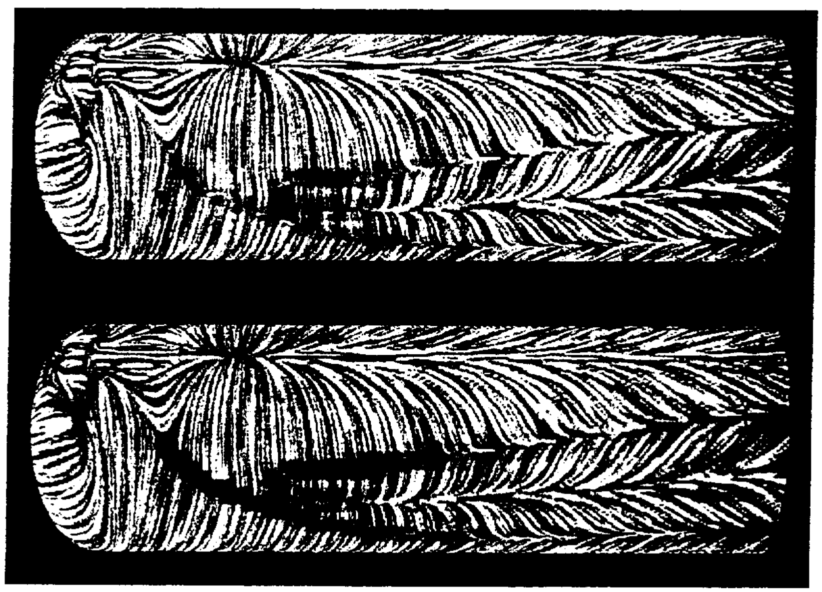

Fig. 1.5. LIC texture colored by velocity angle (top) and by separation and reattachment lines classification (bottom).

1.5 Validation

In the previous section, techniques were described for highlighting flow features automatically. There are several existing algorithms for computing critical points and surface topology [1.6][1.7]. Kenwright has developed an algorithm for computing lines of flow separation and reattachment on solid bodies in a 3D numerical flow fields. [1.8]. To validate the features that are highlighted by the separation and reattachment classification technique, we overlaid the results from these analytical algorithms on the flow texture. Figure 1.7 shows the surface flow topology, which is computed by the flow system developed by Globus et al. (top) [1.7], and the lines of separation and reattachment computed by Kenwright's algorithm (bottom) [1.8] overlaid on the texture computed by our algorithm [1.5].

Note that there is a very good match of the texture highlighted by our technique with the analytical separation and reattachment lines.

Figure 1.8 shows another validation using the delta wing data set.

1.6 Future Direction

Color LIC provides additional insight into the monochrome LIC texture patterns. The choice of scalar function used can change the global appearance of the flow texture. Sometimes, the change in color information is more dominant than the change in flow texture patterns. It is the user's judgment to choose the one that is most appropriate for their applications. Although this paper described some current techniques for automatic flow feature detection/highlighting, there is still a need for LIC algorithms that can provide diversified flow feature detection.

1.7 Acknowledgments

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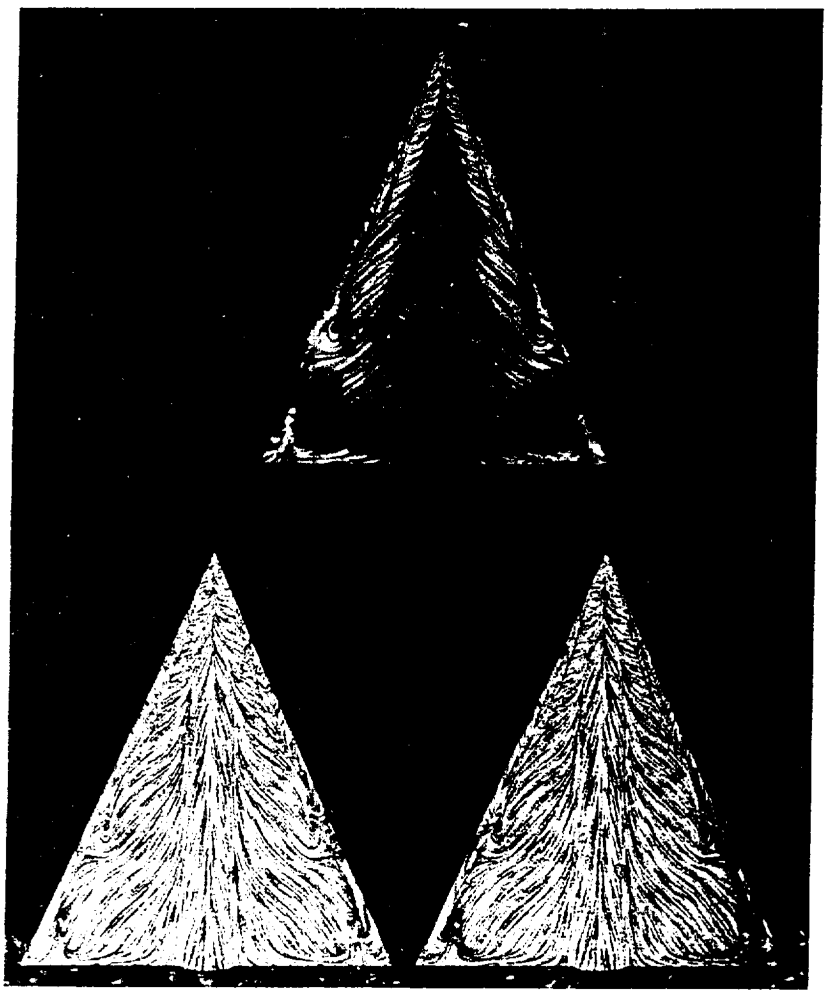

Fig. 1.6. LIC textures colored by velocity direction (top), velocity angle (bottom left) and separation and reattachment line classification (bottom right).

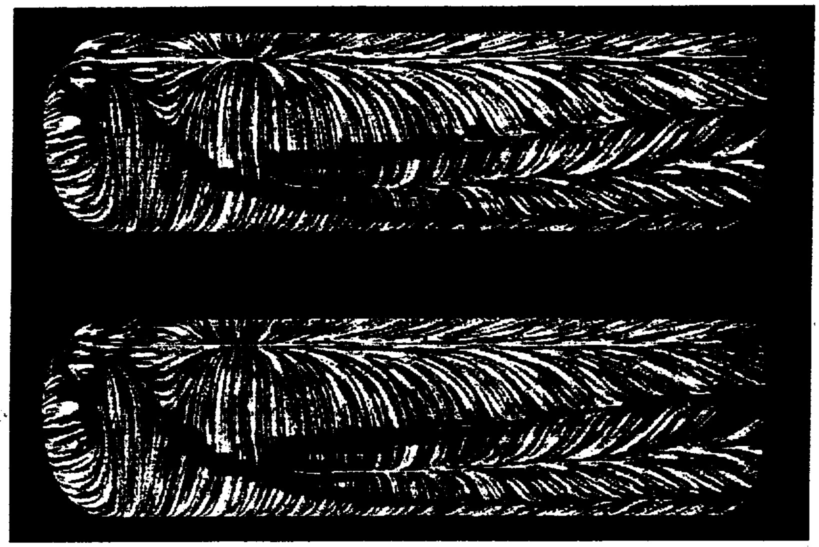

Fig. 1.7. Enhanced color LIC texture overlaid with surface topology (top) and analytical lines of separation and reattachment (bottom).

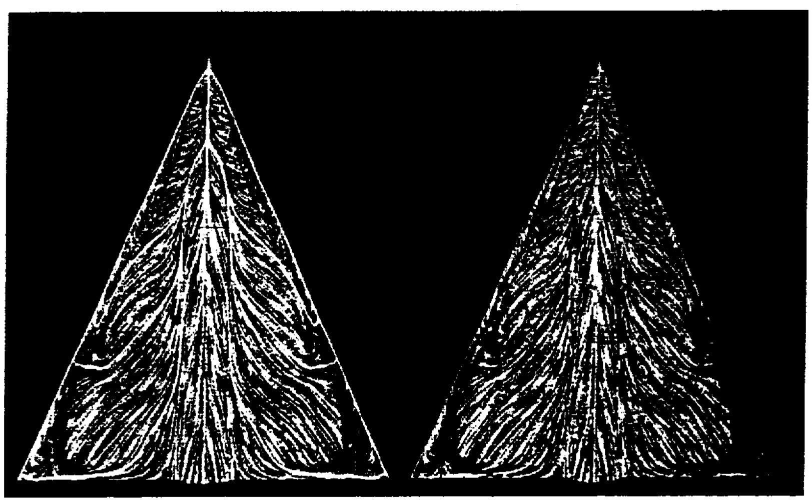

Fig. 1.8. Enhanced color LIC texture overlaid with surface topology (left) and analytical lines of separation and reattachment (right).