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Summary of Work on Shock Wave Feature Extraction in 3-D Datasets

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Abstract

This report discusses a method for extracting and visualizing shock waves from three dimensional computational data-sets. Issues concerning computation time, robustness to numerical perturbations, and noise introduction are considered and compared with other methods. Finally, results using this method are discussed.

Introduction

The visualization of shock waves within transonic, supersonic, and hypersonic flows has been a persistent problem. The difficulty lies in accurately extracting the shock from a computed data-set and presenting a meaningful representation of the results. Accurately extracting and depicting these shocks can lead to improvements in aerodynamic design and an insight into the physics of the flow. Much work has been done on the extraction of features within large data-sets using various data visualization techniques such as isosurfaces, stream ribbons, and contour maps. Recently, work done by Pagendarm and Seitz [1] has been successfully applied towards the extraction of shock waves. Their technique relied on the fact that the density jump across a shock numerically smears across a narrow band. This can be seen in Figure 1a, which represents a 1-D example, where the ξ axis is a location along the shock and ρ is the density. Since $\Delta\xi$ is a rather small distance, the shock can be assumed to be located at the inflection point. This point can be located via the second derivative, $\frac{\delta^2\rho}{\delta\xi^2} = 0$. Figure 1c depicts this derivative. Many numerical algorithms can be applied to extract this zero value. Pagendarm, and Seitz did not use the second derivative directly, since they were dealing with 3-D datasets; instead, they used $\vec{u} \cdot \nabla(\vec{u} \cdot \nabla\rho)$. There are a few difficulties with this method. From a numerical method standpoint, the noise is amplified for each derivative taken. Furthermore, this method requires the gradient to be taken twice, thereby producing many local minima and maxima which are detected by zero-search algorithms. These artifacts can be filtered with some computational effort. Another problem is that this method may cause false detection in free stream regions. The minute perturbations in numerical data in the free stream produce regions where the first and second derivatives

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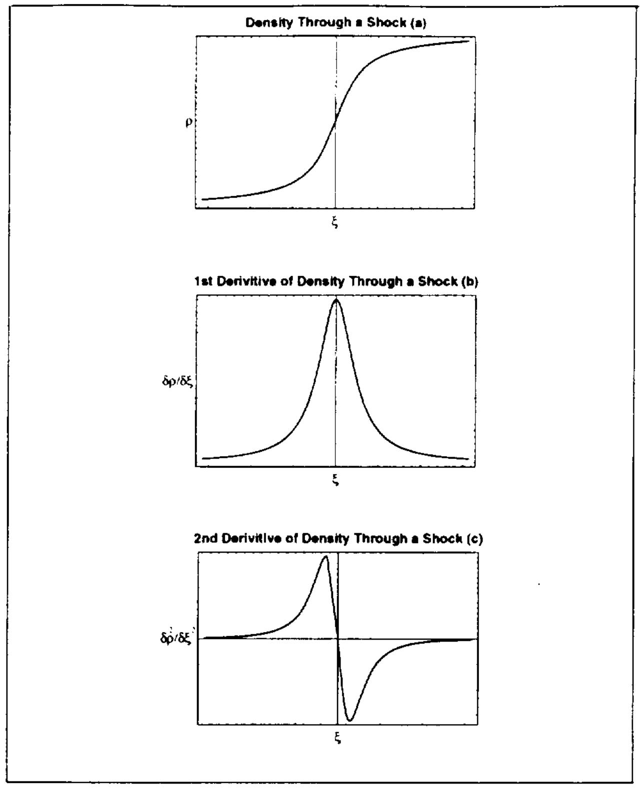

Figure 1: Density variation and its derivatives across a shock wave

appear to cross zero, rather than remaining fixed at zero. This causes zero-search algorithms to tag these points. Pagendarm's and Seitz's algorithm, however, is general enough to be applied to a variety of problems concerning discontinuities. What we propose is a technique that takes advantage of shock attributes for a faster and cleaner extraction. Faster in that we minimize the operation count, and cleaner in that we reduce noise.

Theoretical Background

A shock represents a sudden change of fluid properties. Typically, a shock is witnessed when a body travels at supersonic speeds. The flow adjusts to a body by abruptly changing its pressure, density, and temperature. This abruptness is caused by the flow's inability to sense the body. The Mach number M which is defined as the ratio of stream velocity to sonic velocity can be composed of two components namely one that is parallel $M_{||}$, and the other that is perpendicular $M_\perp$ to a shock wave. The fluid properties such as density, static pressure, and total temperature are distinct on either side of the shock and appear as a jump across the shock. We define $M_\perp$ as follows:

$$M_\perp = \frac{V_\perp \cdot V_\perp}{a^2} \tag{1}$$

where a is the speed of sound and $V_\perp$ is the velocity in the direction of the pressure gradient,

$$V_\perp = V \cdot \frac{\nabla P}{|\nabla P|} \tag{2}$$

The transition of $M_\perp$ across a shock progresses from supersonic, $M_\perp > 1$ to subsonic, $M_\perp < 1$. Equation (1) assumes that the pressure gradient is normal to the shock. We use this assumption in our method for shock extraction.

Several steps are required for the extraction of the shock. We first begin by computing $M_\perp$ for the entire computational space using Equation (1). $M_\perp$ is used, rather than Mach number, to ensure the capture of oblique shock waves. The computational space is composed of grid cells. Each cell, composed of eight neighboring grid points, is checked to ensure the region is in compression $\nabla P \cdot \vec{V} > 0$. Shocks exists only in regions of compression; by removing expansion waves, further computation is not required. A further check to validate the existence of a shock within a cell, is to validate that the change in pressure (δP) is within a safety factor of the Rankine-Hugoniot range. Regions where the pressure gradient changes direction abruptly, thereby producing a large angle between the velocity vectors, can cause $M_\perp$ to drop below 1.0, and appear as a shock. Therefore, using the isentropic relation,

$$\delta P = P * \frac{2 * \gamma}{\gamma + 1} * M_\perp^2 - \frac{\gamma - 1}{\gamma + 1} \tag{3}$$

where $M_\perp$ is the largest in the computational set, we ensure that the pressure gradient is large enough for a shock to exist. If a cell meets these criteria, it is then passed through the marching cube algorithm [2]. Surfaces constructed from triangles of $M_\perp = 1.0$ are created. These triangles are further checked to ensure that the pressure gradient is in fact in the direction of the surface normal. This filters out regions near the body (in the boundary layer) that can be tagged as a shock since the velocity progresses from zero at the body (no slip condition) to free stream velocity, hence passing through $M_\perp = 1.0$. This method of shock detection requires only the first derivative ∇P to be computed, which introduces less noise and is computationally faster than other methods requiring a second derivative. Computation time is further reduced by making simple checks to ensure a region's candidacy for a shock prior to extensive processing. This method is also useful for finding shocks in solutions that have not converged fully. Free stream perturbations will not be tagged since characteristics that are indigenous to flow fields are used. Therefore, this method is not ideal for general 3-D data-sets such as medical imaging data but works best for flow problems.

Results

Several test cases were run to ensure the validity of the method. Figure 2 depicts a lamda shock extracted from a data-set of an ONERA M6 wing [1] with an incoming Mach number, $M_\infty = 0.84$, angle of attack, $\alpha = 6^o$, and Reynolds number, $Re = 761,000$. As can be seen from the figure, we have a clean extraction of the shock with little to no artifacts. The extraction also reveals a region where the lamda shock is separated. This space informs the designer that the solution may not have converged fully, or a higher grid resolution is required in the area. As another verification of the shock algorithm, we extract shock features from a hemisphere cylinder at an angle of incidence of $\alpha = 19^o$, $M_\infty = 1.2$, and $Re = 445,000$). Figure 3 depicts the results. Two distinct shocks exist. The first is the bow shock which is upstream of the nose. The coarseness of the grid yields "holes" in the shock surface. Further

[1]ONERA (Office National D'etuedes Et De Recherches Aerospatiales) wing designed for studies of 3-D flows of low to transonic speeds at high Reynolds numbers.

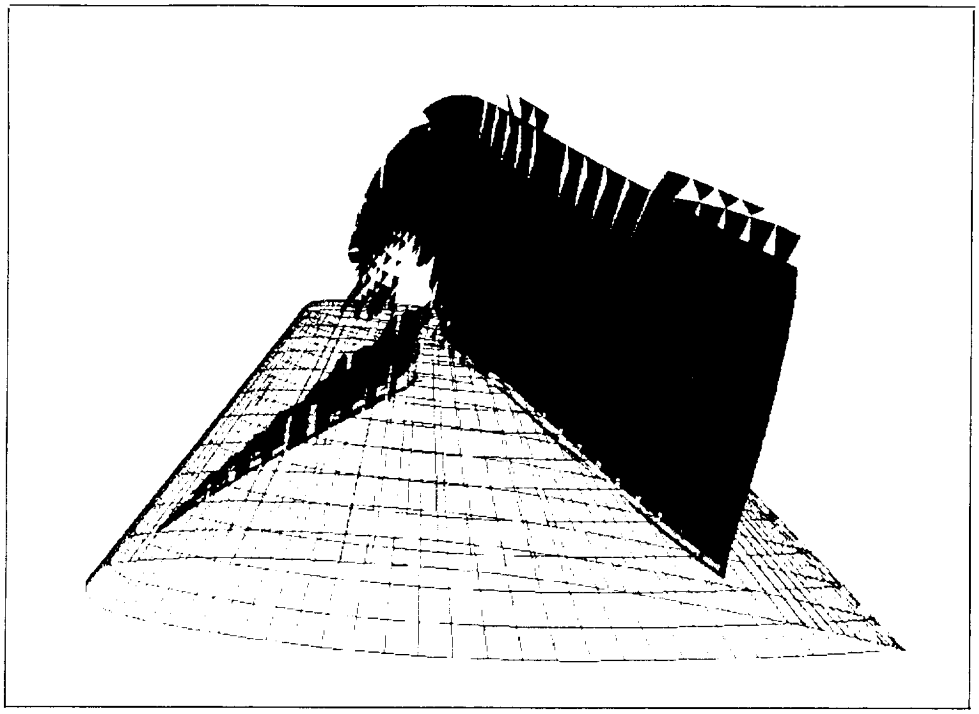

Figure 2: Lamda Shock extracted from ONERA wing.

downstream, along the top surface of the cylinder another shock forms due to the high angle of attack which causes the flow to reach supersonic speed on the leeward side of the body.

Summary

We have devised a method for shock extraction that uses knowledge of the flow to reduce computation time and noise. The basic steps of the method are as follows:

1. Calculate the Mach component in the direction of the pressure gradient ($M_{\perp}$).
2. Verify that the region is undergoing compression.
3. Verify that the pressure gradient within a region is consistent with the existence of a shock.
4. Use the marching cube algorithm to search for $M_{\perp} = 1.0$.
5. Disregard all surfaces whose normal is not in the same direction as the pressure gradient.

Future Work

We plan on extending this work to other significant flow features. The extraction of vortices within a flow will be the first area of study followed by viewing skin friction along a body. The skin friction will be depicted through a simulation oil flow combined with pressure sensitive paint.

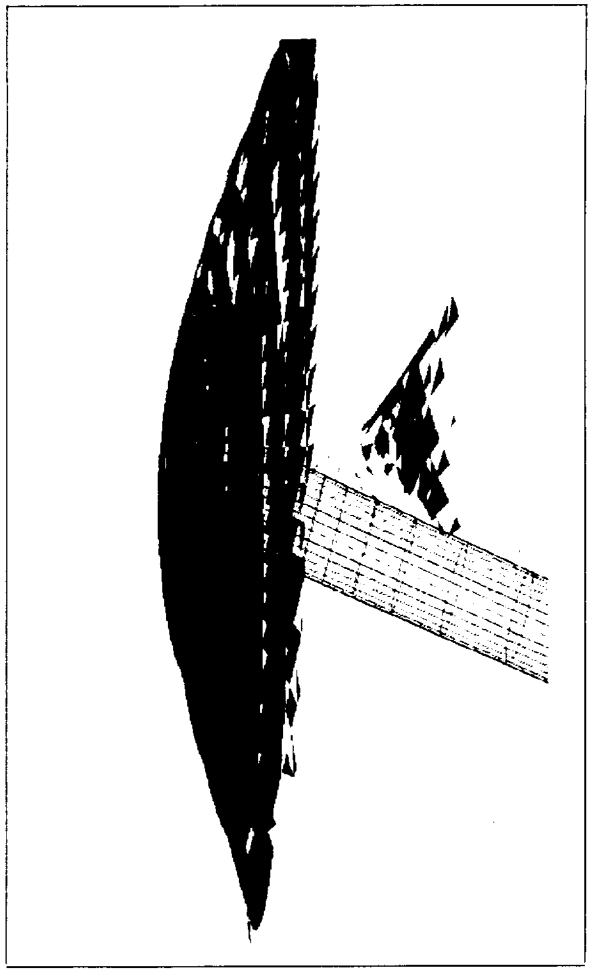

Figure 3: Bow shock with second shock on a hemi-spherical cylinder

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