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MULTISCALE FEATURE DETECTION IN UNSTEADY SEPARATED FLOWS

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Abstract. Very complex flow structures occur during separation that can appear in a wide variety of applications involving flow over a bluff body. This study examines the ability to detect the dynamic interactions of vortical structures generated from a Helmholtz instability caused by separation over bluff bodies at large Reynolds number of approximately 10^4 based on a cross stream characteristic length of the geometry. Accordingly, two configurations, a thin airfoil with flow at an angle of attack of 20^0 and a square cylinder with normally incident flow are examined. A time-resolved, three-component PIV data set is collected in a symmetry plane for the airfoil, whereas direct numerical simulations are used to obtain flow over the square cylinder. The experimental data consists of the velocity field, whereas simulations provide both velocity and pressure-gradient fields. Two different approaches analyzing vector field and tensor field topologies are considered to identify vortical structures and local, swirl regions. The vector field topology uses (1) the Γ function that maps the degree of rotation rate (or pressure-gradients) to identify local swirl regions, and (2) Entity Connection Graph (ECG) that combines the Conley theory and Morse decomposition to identify vector field topology consisting of fixed points (sources, sinks, saddles) and periodic orbits, together with separatrices (links connecting them). The tensor field feature uses (1) the λ_2 method that examines the gradient fields of velocity or pressure-gradient to identify local regions of pressure minima, and (2) tensor field feature that decomposes the velocity-gradient or pressure Hessian tensor into isotropic scaling, rotation, and anisotropic stretching parts to identify regions of high swirl. The vector-field topology requires spatial integration of the velocity or pressure-gradient fields and represents a global descriptor of vortical structures. The tensor field feature, on the other hand, is based on gradients of the velocity of pressure-gradient vectors and represents a local descriptor. A detailed comparison of these techniques is performed by applying them to velocity or pressure-based data and using spatial filtered data sets to identify the multiscale features of the flow. It is shown that various techniques provide useful information about the flow field at different scales that can be used for further analysis of many fluid engineering problems of practical interest.

Key Words. Vortex detection, separated flows, multiscale feature detection, turbulence, LES/DNS, vector field topology, tensor field feature.

1. Introduction

The ability to detect discrete flow structures in fluid flow environments is of growing interest to a wide variety of applications. For instance, large scale flow structures such as swirling, high shear rates regions and vortical structures are thought to be controlling mechanisms for chaotic mixing, unsteady pressure fields that influence fluid-surface interactions, transport in multiphase flows, and a host of other applications. A robust means of developing an understanding of how these flow structures develop, evolve, decay, and interact is of fundamental importance. To achieve this goal there needs to be a quantitative measure of the relevant flow structures. This quantitative measure should also allow for spatial distinction among structures and a means of tracking such structures in the space and time domains. Since there may be many different views on what is a flow structure, there is a wide range of defining conditions for said structures. This results in a number of possible ways of detecting the desired flow structure. The unifying requirement of the detection schemes is that they provide a quantitative measure in a complex flow environment that defines the extent of the structure elements with an acceptable spatial and temporal resolution.

In this study the goal is to identify flow structures that are generated as a result of flow separation that occurs during flow over a bluff body. Such flow separation is indicative of a Kelvin-Helmhotz shearing instability [1, 2, 3] which results in a roll-up along a highly concentrated vortex sheet (or high shear region). Flows of this nature are extremely important in determining the dynamic loading on structures, in aerodynamic flight conditions, and drag forces on man-made vehicles or animals in motion. Presented are results for two such bodies, a thin airfoil at a high angle of attack (angle between the airfoil chord and flight direction is large causing leading edge flow separation) and a square cross section object with separation at both the front and trailing edges. The flow patterns associated with both bodies are illustrated later in this paper, but the common element of concern for these flows is that the flow separation generates large swirling flow structures that are convected downstream as they change in size, shape and intensity.

2. Related Work

Traditionally, flow analysis involving turbulence and unsteady coherent structures that may be imbedded within the broad spectrum of turbulence has been based on collecting one-point and two-point statistics. However, there is a large and growing literature on swirl and vortical flow detection methods [4, 5, 6, 7]. Proper Orthogonal Decomposition (POD) [6], the λ_2 (second eigenvalue) method [4, 8], and the Γ function [9, 7], among others, have been proposed and typically used for flow analysis. Specific identification of vortex structures (or pressure minima) [4, 8, 9] and correlating vortex shedding to leading edge separation [3], have been applied. In addition to these, novel approaches developed in the scientific visualization community based on vector and tensor field visualization and topology extraction provide an alternative means to extract flow structure features [10, 11].

Recent advances in vector field topology focus on features such as fixed points, periodic orbits, and separatrices [12, 13, 14, 15, 16] in two-dimensions, which have been extended to three-dimensional steady state [17, 18, 19], and time-dependent flows [20, 21, 22, 23], respectively. To address noise in the data sets, various flow simplification algorithms have been proposed that are either topology-based [14, 24, 16] or purely geometric [25]. Symmetric tensor field analysis has also been well investigated in two-dimensions [26]. The basic constituents of tensor field topology, the wedges and trisectors have been identified in 2D, symmetric, second-order tensors. By tracking their evolution over time, these features can be combined to form more familiar field singularities (i.e. fixed points) such as saddles, nodes,