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Wavelet spatial scaling for educing dynamic structures in turbulent open cavity flows

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ABSTRACT

In this work a methodology was developed for the selection of wavelet spatial scales to educe dynamic structures in turbulent cavity flows. The wavelet transform was applied to both the temporal signal and spatial fields to extract structures from the oscillating shear layer. The dominant frequencies were identified from the temporal transform of the shear layer oscillations, and then the corresponding wavelength was obtained using the relation $U_cT=\lambda$ at each frequency. The wavelet spatial scaling was examined and a one-to-one relationship was established with respect to the wavelength. At each spatial scale, the transformed images of vorticity, velocity, and pressure fluctuations captured the vortical structures. Using this methodology, the dynamic vortical structures were extracted from the turbulent open cavity flows. Energy analysis was performed to examine the contributions of each structure.

1. Introduction

There has been growing interest in the identification of structures using wavelet transforms. Wavelet transforms offer a multi-scale analysis of turbulent flows. The structures in turbulent flows are well-localized and excited on a wide range of scales; hence, wavelets are powerful tools for identifying dynamic structures in both time and space. Wavelets have compact supports that enable these functions to resolve local features in a flow. Wavelet transforms may be classified into continuous or discrete transforms. The continuous wavelet transform is performed in a smooth continuous fashion and represents the energy content of a signal that contains features on different scales at any instant in time. The discrete wavelet transform is carried out in discrete steps and decomposes the signal into signals with dyadic scales. We employed the continuous wavelet transform to educe structures in turbulent open cavity flows. The present work describes a method for the detection of coherent structures, and considerable effort has been applied toward investigation of the structures life cycles inside a cavity.

Farge (1992) and Farge et al. (2001) used a wavelet transform to study coherent structures in turbulence. The inverse wavelet transform was applied, and scale-specific regions of high vorticity concentration were reconstructed from DNS data to understand the dynamics of the structures. Farge and Schneider (2001) and Roussel et al. (2005) demonstrated two different ways of extracting coherent vortices using orthogonal and biorthogonal wavelets and established a model known as coherent vortex simulation. Rinoshika and Zhou (2005) and Zhou et al. (2006) used a multiresolution technique based on orthogonal wavelet transforms for the extraction of coherent structures. They analyzed the flow behind a cylinder, a turbulent far wake, as well as a near wake, and decomposed these flows into wavelet components based on the characteristic or central frequency f_o. The vortical

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Nomenclature

a_s	wavelet spatial scale
a_t	wavelet spatial scale
D	cavity depth
f	frequency
L	cavity length
Re_D	Reynolds number, $U_\infty D/\nu$
Re_θ	Reynolds number, $U_\infty \theta/\nu$
U_C	convection velocity
U_m	mean velocity
U_∞	free-stream velocity
u_τ	friction velocity
W_g^1	one-dimensional wavelet transformed coefficient of any signal g
W_F^2	two-dimensional wavelet transformed coefficient of any signal F
δ	boundary layer thickness
θ	momentum thickness of incoming boundary layer
λ	wavelength
ω	vorticity

structures were extracted at the central frequency and its dyadics (f_o, $2f_o$, $4f_o$ …). Recent applications of the continuous wavelet transform to turbulence were reported by Ruppert-Felsot et al. (2009) and Narasimha and Bhattacharyya (2010). The majority of previous work on coherent structure extraction using wavelets employed the discrete wavelet transform, in which wavelets were discretely sampled in multiples of 2. Due to limitations in the discrete version of the wavelet transform, the structures could be educed only on the dyadic scales. The wavelet transform essentially captured regions of high activity at any prescribed scale. It may be possible to extract regions of high activity at scale multiples of 2 in turbulent flows, but this may not be sufficient to conclude that the structures shed behind an obstacle at the dyadic of the central frequency are characterized by dyadic spatial scales.

The continuous version of the wavelet transform is richly redundant due to the freedom in the choice of wavelet scale. This quality also facilitates analysis. The transform is particularly useful because it can identify localized regions of energy concentration. This property represents a significant advantage over conventional Fourier-type analysis, which provides only a global estimate of the distribution of energy. Wavelet analysis can detect regions of high activity at different physical scales. Kailas and Narasimha (1999) obtained structures at different scales in mixing layers and turbulent jets from Schlieren images and experimental data, respectively. They identified the regions of high activity at particular scales. The basis by which the wavelet spatial scales were selected for the eduction of structures was unclear in that work; they were unable to obtain circular vortical structures in their transformed images of mixing layers. Recently, Schneider and Vasilyev (2010) summarized existing wavelet-based numerical algorithms in computational fluid dynamics.

The presence of an open cavity in a turbulent flow generates velocity and pressure fluctuations that may induce strong vibrations in the substrate over which the fluid is flowing. The shear layer is separated at the leading edge of the cavity and experiences a Kelvin–Helmholtz instability, which results in oscillations in the shear layer. These oscillations generate well-organized vortical structures that further impinge on the trailing edge, and may produce self-sustained oscillations under certain conditions. Aly and Ziada (2010) examined the self-excitation mechanism of the acoustic diametral modes of an axisymmetric internal cavity–duct system. In incompressible turbulent flows, however, it has not been easy to identify coherent structures that are responsible for the oscillations due to both incompressibility and turbulence. The absence of acoustic resonance leads to weak oscillations of the separated shear layer and the coherent structures are mixed with the inherent turbulent motions (Lee et al., 2008, 2010). Many studies have attempted to extract coherent structures from turbulent open cavity flows. Pereira and Sousa (1994, 1995) observed periodically oscillating shear layers over an open cavity. Lin and Rockwell (2001) performed water tunnel experiments and suggested that large-scale vortical structures were responsible for self-sustained oscillations. Chatellier et al. (2004) observed oscillations in the mixing layer in their experiments, and they theoretically analyzed the fluctuating behavior of the turbulent cavity flows at low Mach numbers. Ashcroft and Zhang (2005) observed the shedding of large-scale vortical structures by Galilean decomposition of the instantaneous and fluctuating velocity fields. Recently, Kang and Sung (2009) and Lee et al. (2008) observed organized structures using proper orthogonal decomposition in their experiments and simulations, respectively.

The present work proposes a selection criterion for wavelet spatial scales for the eduction of coherent structures produced by oscillating shear layers in turbulent cavity flows. The dominant frequencies and time period of the shear layer oscillation can be obtained from the temporal wavelet transform of the vertical velocity component. The wave equation $U_cT=\lambda$ yields the corresponding wavelength of the structure produced, where U_c is the convection velocity. When the spatial wavelet transform is applied, the wavelet spatial scale holds a one-to-one relationship with the wavelength of the spatial structures. Here, the relationship was established at $a_s=\lambda/5$ for the Mexican hat wavelet, where a_s is a wavelet spatial scale. The spatial structures extracted from the vorticity, pressure, and velocity data possessed the specific frequencies observed in the shear layer. Furthermore, the energy contributions of structures at each scale were computed. In later sections, the one-to-one relationships between the wavelet temporal scale (a_t) and the time period of oscillations (T), and between the wavelet spatial scale (a_s) and the wavelength (λ), will be established. The methodology was validated by applying it to a low Reynolds number flow. Only two distinctive vortical structures were observed behind a flexible filament. Large eddy simulations (LESs) were performed over an open cavity at $\mathrm{Re}_D=12\,000$, and the dynamic structures were extracted using the wavelet transform.