Reynolds stress tensor and pressure-related turbulence transport terms measured by time-resolved tomographic-PIV

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Abstract

Turbulence is inherently a three-dimensional and time dependent flow phenomenon (Pope, 2001). Because of the ubiquitous existence of turbulent flows in nature, accurate characterization of turbulent flows, either through experimental measurements or through direct numerical simulations, is of paramount importance for modeling turbulence (Liu and Katz, 2018). Since its inception in 1984 (Adrian, 1984), Particle Image Velocimetry (PIV), among several other conventional techniques used for turbulence measurements, has been a valuable tool for providing reliable experimental data for turbulence research. Several advancements in hardware such as high-speed cameras, together with innovative algorithms and procedures, have extended the scope of PIV to a variety of applications. Westerweel et al. (2013) point out in a recent review article that one of the main advantages of the PIV measurement is its unique ability in measuring quantitatively spatial derivatives of the flow field. With the development of Tomographic PIV introduced by Elsinga et al. (2006), it is now possible to measure simultaneously the distributions of three velocity components in a three-dimensional flow field, thus enabling us to measure all the velocity derivatives of a turbulent flow. However, for a thorough characterization of a turbulent flow, in addition to the velocity gradients, the instantaneous pressure distribution in the 3D flow field also needs to be measured.

The instantaneous pressure distribution in a turbulent flow field can be measured non-intrusively by integrating the measured material acceleration using particle image velocimetry (PIV), as demonstrated by Liu and Katz (2006, 2008, 2013), Joshi et al. (2014), Van Oudheusden (2008) and Ragni et al. (2009), to name a few. The pressure can also be obtained by solving the Poisson equation, as shown in Violato et al. (2011), and De Kat and Van Oudheusden (2012). Review and comparison of the two pressure reconstruction approaches can be found in Charonko et al. (2010) and Van Oudheusden (2013). Liu and Moreto (2020) demonstrate the robustness and low noise sensitivity of the rotating parallel ray omnidirectional integration method, which is capable of measuring the instantaneous pressure distributions at high accuracy in a complex turbulent flow field. Coupled with the time-resolved Tomographic PIV, the pressure reconstruction method enables the experimental characterization of all the terms including the pressure-related turbulence transport terms in the Reynolds Stress Transport equation.

Liu and Katz (2018) applied planar PIV in conjunction with the virtual boundary omni-directional integration to the study of a shear layer flow impinging on a cavity trailing corner at a Reynolds number of 4×10^4. They found that the distribution patterns of the pressure diffusion and the turbulence diffusion differ considerably, indicating that the conventional modeling for the transport terms is not adequate, at least for the turbulent shear layer flow over a cavity. Their results also show that the turbulence fluctuation energy is redistributed from the streamwise component to the lateral ones, and this intercomponent energy transfer has an important impact on the flow dynamics around the cavity trailing corner area. However, due to the limitation in planar PIV, they can only infer indirectly the spanwise intercomponent turbulence energy transfer based on the measured streamwise and wall normal components of the pressure-rate-of strain terms. In this paper, we will demonstrate the capability of measuring simultaneously all the Reynolds stress tensor components and the instantaneous three dimensional distribution of pressure for a cavity flow at a Reynolds number of 4×10^4 by Time-Resolved Tomographic PIV. The free stream velocity is set to 1.2 m/s, which is identical to the Hopkins experiment (Liu and Katz, 2013, 2018). The 2D cavity geometry is 38.1 mm long, 101.6 mm wide and 30.0 mm deep, with the beginning part of the upstream ramp machined with tripping grooves. Except the width, the geometry of cavity is also identical to that of the Hopkins cavity setup, thus facilitating comparison and validation of the new Tomo-PIV measurement results. Preliminary results on

the Reynolds normal stress measurement around the cavity trailing corner based on a limited sample of 149 instantaneous realizations (thus not converged yet) are shown in Figure 1. Time-averaged pressure distribution around the cavity trailing corner based on 4076 realizations (also not converged yet) is shown in Figure 2. The selected image acquisition rate (4996Hz) is sufficient to resolve the Kolmogorov time scale based on a curve fit to the spatial energy spectra (Liu and Katz, 2013, 2018), according to which, the Kolmogorov length scale is 26 μm and the Taylor transverse microscale is 0.5 mm. The size of the Tomo-PIV measurement volume in the current study is approximately $42.6 \times 11.7 \times 6.9$ mm^3 to maintain sufficient resolution. In the current experiment, an interrogation volume of 40 pixel × 40 pixel × 40 pixel, which corresponds to 0.84 mm × 0.84 mm × 0.84 mm in physical dimension, is compatible with the Taylor transverse microscale, but one order of magnitude larger than the Kolmogorov length scale. A 75% overlap between the interrogation windows gives a vector spacing of 0.21 mm. In this paper, based on 140,000 instantaneous 3D realizations of the cavity flow, we will present converged turbulence statistics on all terms in the Reynolds stress transport equation, with an emphasis on the characterization of the magnitude of the intercomponent turbulence energy fluctuations represented by the pressure-rate-of strain terms, so as to verify the conjecture raised in Liu and Katz (2018) about the magnitude of the third component of the intercomponent energy transfer.

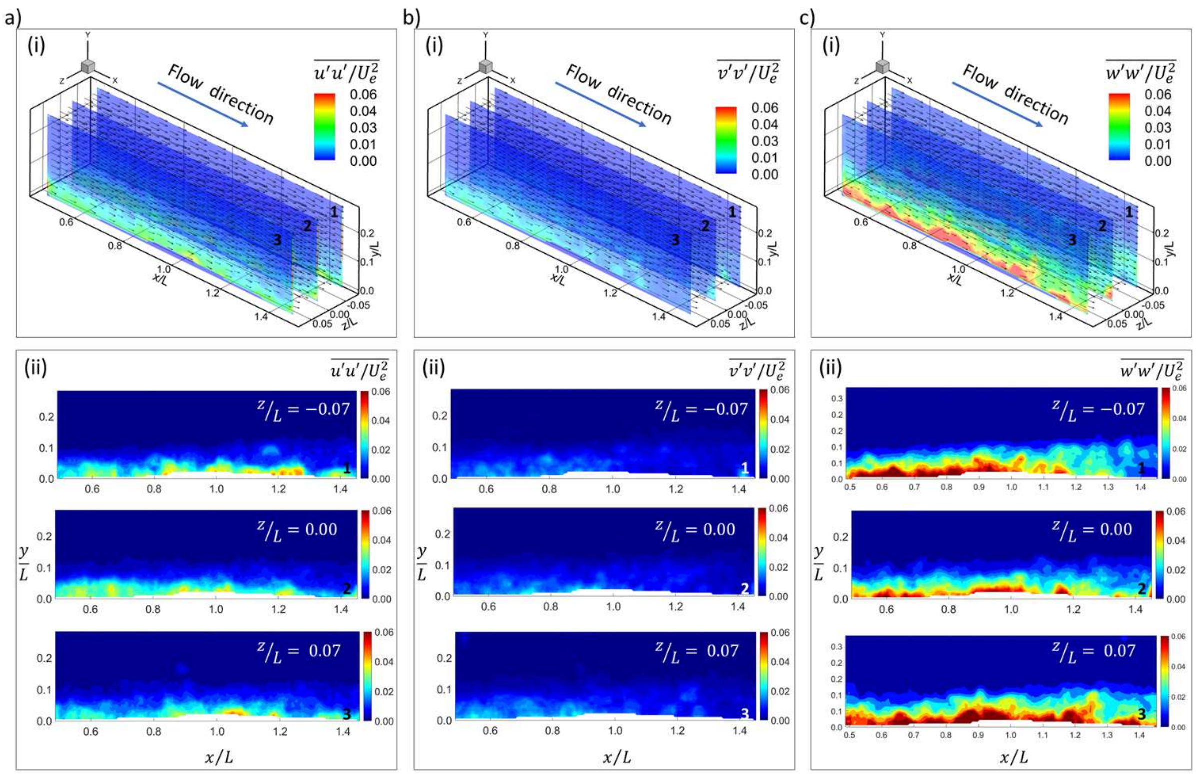

Figure 1: Normal Reynolds stress profiles based on 149 realizations of Tomo-PIV measurement over a cavity trailing corner at a Reynolds number of 4×10^4 (a) $\overline{u'u'}$, (b) $\overline{v'v'}$, (c) $\overline{w'w'}$ distributions, which consist of, (i) 3D distributions, and (ii) planar contours at three selected spanwise planes that are located at the center of the measurement volume, and at the places close to the two edges of measurement volume in the spanwise direction, respectively.

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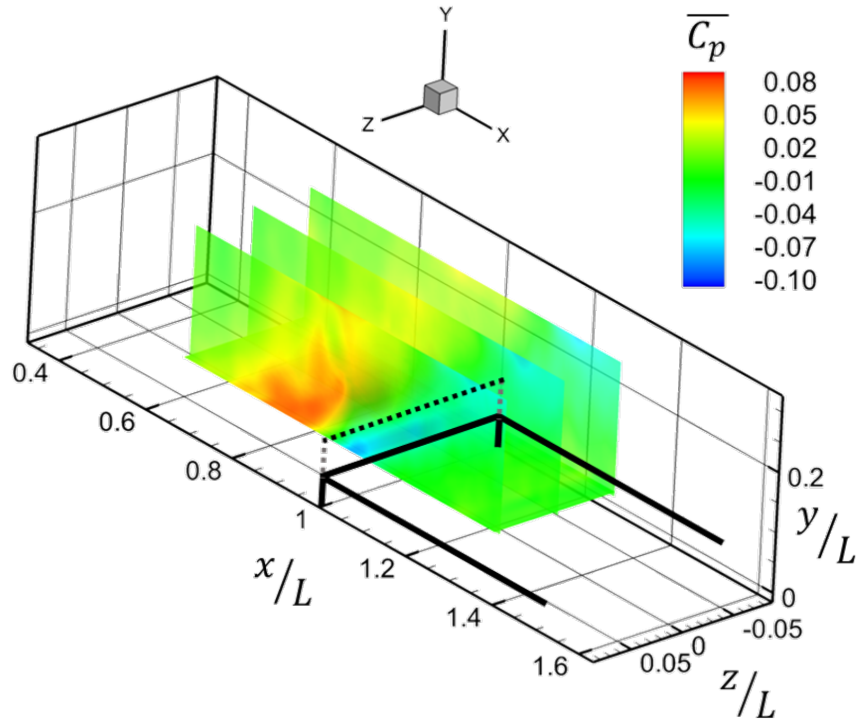

Figure 2: Time-averaged pressure distribution around the cavity trailing corner based on 4076 realizations.

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