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Evaluation of a film-based wall shear stress measurement technique in a turbulent channel flow

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ABSTRACT

Mean wall shear stress in a turbulent channel flow has been measured using a film-based shear stress sensor with a working principle based on the deformation of a thin elastic film. A direct comparison was made between the elastic film measurements and those using oil-film interferometry in the same experimental facility to evaluate the capability of the novel technique to measure the mean wall shear stress. The results indicate that the film-based sensor measures the wall shear stress within the uncertainty of the oil film measurement for the range of Reynolds numbers considered here, i.e. 2100–2900 based on the friction velocity and the half channel height.

1. Introduction

Due to the importance of accurate measurements of the wall shear stress in wall-bounded turbulent flows, significant efforts have been made to develop precise instrumentation for this purpose in recent decades. The mean wall shear stress is used to determine viscous drag and is essential to scale turbulence statistics in wall-bounded turbulent flows. The preferable direct measurement of the wall shear stress is primarily performed using floating elements fabricated using either conventional or MEMS-based approaches [19,9,14]. In recent years, by means of the application of flexible materials, a novel type of sensors has been proposed to measure the mean and fluctuating components of the wall shear stress in two dimensions. These approaches include micro-pillars [3,8] and film-based shear stress sensors [6,2].

A film-based sensor offers a direct measurement of the wall shear stress in a non-intrusive manner. This technique has the capability of measuring the instantaneous two-dimensional wall shear stress in air or water environments. In addition to the sensor application in flows over a flat plate, it can be employed in more complex surface flows such as those with separation, reattachment, and reverse flow where the application of other techniques is limited or not feasible. For instance, it can be used in a backward-facing step flow configuration or in the surrounding of an object like a cylinder in a cross flow or be embedded in curved surfaces like in an airfoil or a turbine blade.

The measurement of the wall shear stress based on the development and application of a film-based shear stress sensor has been previously reported in Amili and Soria [2]. In that study, an indirect measurement of the wall shear stress using PIV was also addressed. In the present study, oil-film interferometry (OFI) as a mature and well-established wall shear stress measurement technique is used to further evaluate the wall shear stress results obtained with the elastic film.

2. Experimental setup and methodologies

2.1. Flow facility

Measurements have been performed in the wind tunnel facility located in the Laboratory for Turbulence Research in Aerospace and Combustion (LTRAC) at Monash University. A detailed description of the flow facility and the experimental techniques employed in this work can be found in Amili [1]. Here, only a very brief description is provided. The channel flow facility has a working section with a length of 4.6 m and a width of 1 m with the width to height ratio of 9.75:1. A grid at the inlet of the working section ensures a fully developed turbulent flow at the measurement section. Flow statistics obtained from planar PIV confirm the existence of a log region in the velocity profile taken at the center plane of the measurement section and show the presence of fully developed

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turbulent channel flow [1]. Experiments were carried out at six Reynolds numbers in the range of 2100–2900 based on the friction velocity (u_τ) and the half channel height ($H/2$), $Re_\tau = u_\tau(H/2)/\nu$, where ν is the kinematic viscosity. The Reynolds number is in the range of 90,000–130,000 based on the bulk velocity ($\overline{U}$) and the full channel height (H), $Re_m = \overline{U}H/\nu$. In all cases, the turbulence intensity at the channel centerline is approximately 3.5% based on the streamwise and wall-normal velocity fluctuations.

2.2. Film-based sensor setup

The film-based sensor studied here utilizes the deformation of a thin elastic film to measure the wall shear stress. A silicon-based film with a shear modulus of $G = 84$ Pa and a thickness of $h = 1$ mm was used as the shear stress sensor. The film was formed in a cavity with dimensions of 100 mm × 70 mm in an acrylic insert. The bottom surface of the cavity is made of glass, and the depth of the cavity can be adjusted. The cured material is firmly attached to the bottom and side surfaces of the cavity. The sensor was flush mounted with the lower wall of the working section approximately 41 channel heights downstream of the test section entrance. The geometry and mechanical properties of the film were accurately measured, and particles with the nominal size of 11 μm diameter were embedded on the film's top surface to act as markers. An array of LEDs was used as the light source which provided excellent uniform illumination of the film and high signal-to-noise ratio of the reflected light of particles [4]. The film was imaged using a 12-bit PCO. Pixelfly camera with a CCD size of 1280 px × 1024 px with a pixel size of 6.7 μm × 6.7 μm. The use of a 55 mm Nikon Micro-Nikkor lens in combination with extension rings yielded an imaging resolution of 5.82 μm/px, i.e. a magnification of 1.15. A schematic of the experimental setup is shown in Fig. 1. A second imaging system in the same configuration (not shown in this figure) was used to account for the rigid-body movement of the wind tunnel.

Film deformation was calculated using the optical measurement of the film under flow-on and flow-off states. For this purpose, a multi-grid cross-correlation digital particle image velocimetry (MCCDPIV) algorithm developed by Soria [16] was employed. Multi-passing with the final interrogation window size of 32 px × 32 px with 50% overlap yielded sub-pixel accuracy (using 2D Gaussian peak-fitting function) that enabled measurements with a high dynamic range. Following the calculation of the film's local strain (γ) under flow loading, the local wall shear stress (τ) was computed using the stress–strain relation obtained from the sensor calibration. The film deformation in the image plane is in the range of 1–2 pixel. The static calibration of the sensor indicates a homogeneous and isotropic film with a linear elastic solid behavior in the range of applied loads. It is worth emphasizing that the sensor measures the local displacement of the elastic film, and thus the measurement is spatially resolved. A sub-region of the film and the corresponding wall shear stress map are shown in Fig. 1.

To estimate the effect of the film's borders on the displacement distribution, a numerical simulation of the sensor was performed. The governing equations of the film with geometry and mechanical properties similar to a fabricated sensor were solved using the OpenFOAM® platform under different loading conditions. Fig. 2 shows the normalized horizontal and vertical deformations across the length of the film under a uniform shear of 1 Pa. The

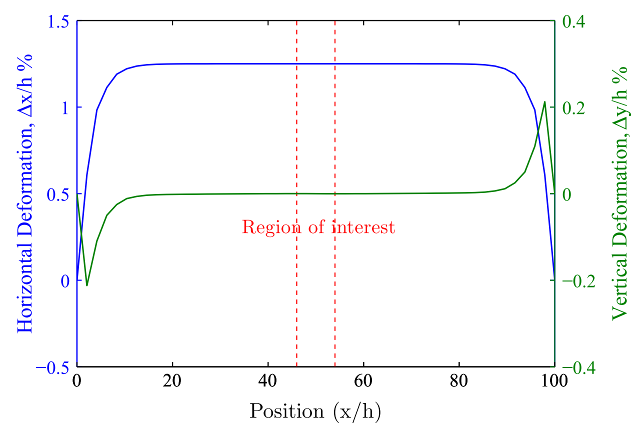

Fig. 2. The normalized tangential and normal displacements along the length of the film under unit uniform tangential stress.

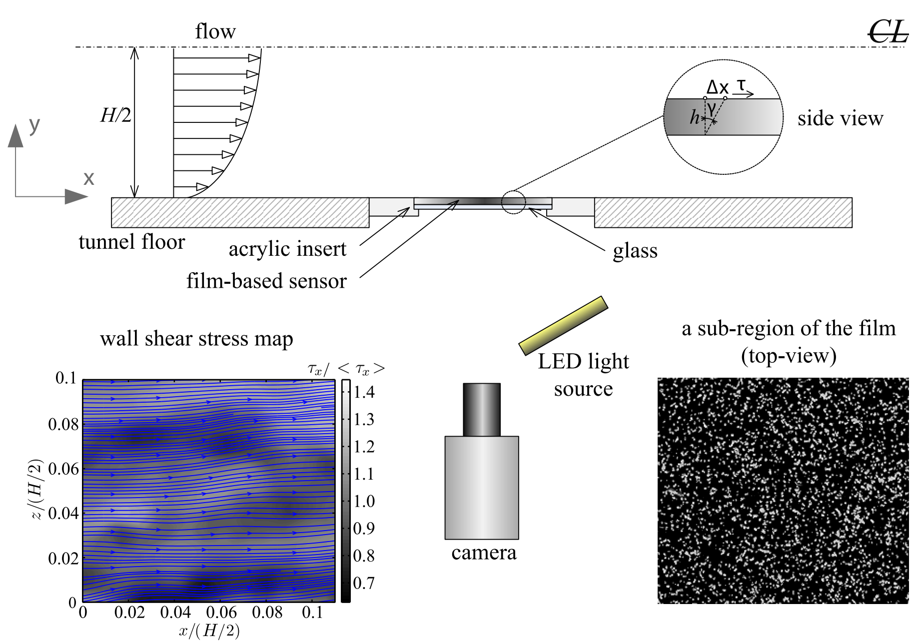

Fig. 1. A schematic diagram of the experimental setup for the wall shear stress measurements using a film-based shear stress sensor. Note that the dimensions are not to scale.