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Local surface shear stress measurements from oil streaks thinning rate

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ABSTRACT

This paper presents an approach to evaluate the time-averaged local shear stresses based on the analysis of video images of oil streaks. The time-averaged deformation rate of thin oil streaks, deposited on a model exposed to an air stream, increases pro rata with the skin friction, while it is inversely proportional to the viscosity. Hence, the oil viscosity represents an important parameter in the method to be carefully characterized and selected for the level of aerodynamic skin friction, flow velocity, and time interval to be resolved. Post-processing image techniques were applied to reconstruct the rate of change in the oil thickness from oil streak length monitored by a high-speed camera. The present technique was demonstrated on a model exposed to subsonic and supersonic flows, and results were compared with theoretical calculations. The present measurement procedure offers ancillary information to the conventional qualitative oil dot visualizations, providing the wall shear stresses at a reduced cost and complexity.

1. Introduction

Surface shear stress data is essential in a wide range of contexts and applications involving flow/surface interactions. Skin friction information is essential in pipe flow systems from industrial to biological and medical applications, for efficient aerodynamic vehicles, in flow control applications, and any fundamental aerodynamic issue. The importance of skin friction data has motivated a continuous effort during the last decades to develop reliable measurement techniques. Several direct and indirect methods have been proposed with competing requirements like extensive measurement regions, sensors miniaturization, or measurement response characteristics. Previous authors [1–4] have presented reviews on the potentials and limitations of the main experimental approaches, including: Preston tubes, Micro Electro Mechanical Systems such as piezoresistive microcantilevers [5,6] and thermal sensors [7], liquid crystals, wall-wire measurements or interferometry thin-oil-film techniques. During the past years, advancements on sensor miniaturization, image acquisition and computing capabilities have inspired improvements in well-established experimental skin friction methods [30]. On the other hand, oil dots visualization is a well-established qualitative technique to reveal flow separation, secondary flows, and boundary layer transition (Langston and Boyle [8], and others [9,10]).

The present methodology is actually based on the deformation of an oil film as described by the lubrication theory. During the test a high-speed camera records the temporal deformation of the oil droplets. Then, image post-processing of the successive frames allows the determination of the oil streak thickness variation, and subsequently the skin friction. The described procedure is limited to flows without strong spatial shear stress gradients and three dimensional effects. The applicability of the technique was demonstrated in subsonic and supersonic flows at the von Karman Institute for Fluid Dynamics (Belgium), and results compared with theoretical correlations. The proposed technique is supplementary to oil-dot visualizations, offering skin friction data at the additional cost of high resolution image sampling using a high-speed camera.

2. New approach for wall shear stress measurements

2.1. Theoretical background

The deformation of an oil thin film on a surface, within a boundary layer, is sensitive to wall shear-stress, gravity, pressure gradients, and surface tension effects. Under certain conditions the oil deformation responds primarily to the wall shear stress

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generated by the airflow, thinning at a rate proportional to the shear stress magnitude. Squire [11] derived an original theoretical study of the thin film equations, which were then exploited by Tanner and Blows [12] to develop interferometry-based techniques. The assumptions to derive the general thin film differential equation are:

- the oil flow is two-dimensional, incompressible, and has a slow viscous motion
- the air boundary layer thickness is greater than the oil thickness
- the pressure can be assumed constant across the oil film thickness.

The coupling of the air boundary layer and oil flow is achieved through the boundary condition at the air–oil interface. As the oil film thins, the relative magnitudes of gravity forces, pressure gradients and surface tension effects decrease. Hence the oil film motion is dominated by the wall shear stresses, Eq. (1).

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x}\left(\frac{\tau_w h^2}{2\mu}\right) = 0 \tag{1}$$

In Eq. (1) h is the local film height, τ_w is the wall shear stress, μ is the oil viscosity, and the x coordinate is aligned with the skin friction. When the shear-stress gradient in the x direction is negligible, a linear solution of Eq. (1) can be obtained (Eq. (2)), assuming as an initial condition that the oil thickness is large at $t=0$ ($x=0$ at the leading edge) and that the oil viscosity is constant. The validity of the initial condition has been numerically demonstrated [13,14] for different initial oil cross-sectional shapes, proving that the error of the linearized solution diminished rapidly as the oil thins. In regions of high shear stress gradient, Ruedi et al. [15] and Pailhas et al. [16] proposed the use of small oil droplets to cut out those regions in small area elements, over which the wall shear stress can be considered constant.

$$h(x,t) = \frac{\mu \cdot x}{\tau_w \cdot t} \tag{2}$$

Segalini et al. [17] propose corrections to the conventional similarity solution (Eq. (2)) addressing a velocity discontinuity at the interface air/oil where a Couette flow within the oil is responsible of a small velocity discontinuity that must be compensated by an internal boundary layer developing above the oil drop. While thinner oil films are subjected to shear stresses closer to those of the air flow in the absence of oil, the oil thickness must remain over a certain value below which the lubrication approximation theory is no longer valid [18].

Based on Eq. (2), the wall shear stress can be obtained from the measurement of the oil film slope. Although steady force fields were assumed initially in the development of the equations, Murphy and Westphal [19] demonstrated that the oil film responds instantaneously to frequencies up to 10 kHz, providing an accurate average skin friction also in turbulent flow fields. The evaluation of the linear relation (Eq. (2)) at two instants (t_1 and t_2) yields the shear stress in function of the oil slope and viscosity (Eq. (3)):

$$\tau_w = \mu \frac{1/s_2 - 1/s_1}{t_2 - t_1} \tag{3}$$

Considering an oil streak along the x direction at a given instant, Fig. 1 Figure sketches the relevant parameters required in the present method. The film slope s is the ratio of maximum oil thickness (h, close to the oil streak trailing edge) to length (a fraction of L). Although two instants (t_1 and t_2) suffice to evaluate the skin friction, multiple images increase the accuracy of the method.

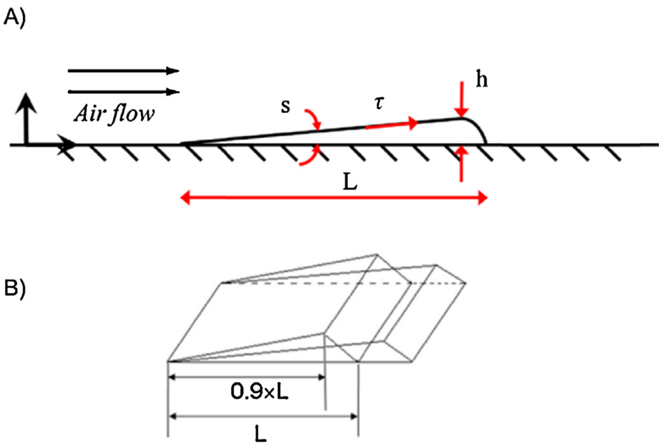

Fig. 1. (A) Sketch of the lateral cross section of the oil thin film. (B) Assumed oil-dot film shape.

2.2. Methodology

Prior to the test, tiny oil droplets should be deposited onto the model surface. During the test run, the oil dots deform into thin oil streaks aligned with the local wall shear stress. The evolution of the wetted area of the oil thin film is recorded by a digital video camera. The thickness of the oil dot is reconstructed from an assumption of the lateral cross section shape (see Fig. 1) and top surface shape, the instantaneous surface area, and the initial volume of the oil droplet. The shear stress is determined from the oil film slope variation and viscosity of the oil mixture. A triangular lateral cross section is considered, in agreement with the solution of the governing equation of the thin-film at constant shear stress [14]. Multiple studies have addressed the hydrostatic shape, transient deformation, and asymptotic shape of small liquid drops concluding that when the droplet volume and capillarity are small, the final shape is flat and the motion of the fluid is accurately described by the lubrication flow theory [20,21]. Furthermore, in the present investigation the oil dot triangular cross sectional shape was monitored during several tests, driving to the consideration of the triangle apex to be at 90% of the film length from its leading edge, as sketched in Fig. 1B. A rectangular shape is considered for the top surface of the oil film in agreement with the previously mentioned studies on droplets deformation morphology, and with the present oil film evolution recordings. Pixel averaging is performed at the borders of the oil film recordings to determine the film length at each time instant. From the computed oil film thickness and length at the apex of the triangular shaped oil film at different time instants, the shear stress is determined from the oil film slope variation and viscosity of the oil mixture.

Fig. 2 displays the length to height ratio of two oil dots submitted to a subsonic flow in function of time, considering a time window ranging from 4 s to 10 s. For this particular test, and selected oil viscosity, from time 0 s to 4 s the oil droplet was not thin enough to fulfill the thin-film theory hypothesis. The slope of the linear fit of this temporal evolution is the shear stress divided by the oil viscosity. The regression coefficients of the linear fits (R^2) stated in Fig. 2 correspond to the represented time window. Maps of regression coefficients were built for each test in order to confirm the linear assumption and to optimize the time window considered for the data processing.

2.3. Video processing and analysis

Fig. 3 summarizes the image processing tool implemented in Matlab® to provide the local shear stress based on the video