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Technical Notes

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Two-Point Measurements of Wall Shear Stress Beneath an Axisymmetric Separating/Reattaching Flow

Yongxiang Li,* Ahmed M. Naguib,† and Laura M. Hudy‡
Michigan State University,
East Lansing, Michigan 48824

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Introduction

MEASUREMENT of the space–time characteristics of the unsteady surface shear stress and pressure in separated flows is significant for validation of computational codes, developing physics-based models of flow-induced noise and vibration, and feedback flow control. Examples include validation of the computed surface stress signature of the large-scale structures in a large-eddy simulation and development of low-order models for estimating the flowfield from surface measurements to provide nonintrusive, flow-state information in feedback control of a separated flow.

Although there has been a wealth of information on single- and multipoint measurements of the unsteady surface pressure p' beneath canonical and noncanonical separation bubbles (e.g., Cherry et al. [1], Heenan and Morrison [2], Lee and Sung [3], Hudy et al. [4], and Greenblatt et al. [5]), the same is not true for the surface shear stress τ'. This is caused by the difficulty in measuring the *direction-reversing* shear stress beneath the separation bubble. Fernholz et al. [6] did a comprehensive review of wall-shear-stress measurement techniques and concluded that only wall hot wires (i.e., hot wires placed in the viscous sublayer but not in contact with the wall) and pulsed wires (Westphal et al. [7]) were capable of measuring the unsteady wall shear accurately. However, wall hot wires can not be used in cases involving flow reversal. Wall pulsed wires, on the other hand, measure the wall-shear magnitude and direction, but their frequency response is limited to tens of hertz.

In recent years, a number of studies sought to overcome the difficulty in measuring the wall shear stress in separated flows by developing new sensing approaches. In particular, Spazzini et al. [8] developed a wall-mounted double hot-wire probe; Tihon et al. [9] reported measurements using a three-segment electrodiffusion probe in a water channel; and Li and Naguib [10] employed a high-frequency oscillating hot wire (OHW). All of these studies reported *single-point* measurements in a backward-facing-step flow. Although this information is useful in understanding the temporal behavior and single-point statistics of the wall shear stress, it does not reveal the associated space–time behavior. To capture this behavior, the present investigation employs two OHW sensors to obtain the two-point, streamwise wall-shear-stress correlation in an axisymmetric backward-facing-step flow. The results are compared with their counterpart based on surface-pressure measurements on the same model.

Experimental Setup

The axisymmetric, backward-facing-step model is formed from a cylindrical surface that abruptly steps down in diameter from 0.124 to 0.10 m at 1.214 m downstream of the model's hemispherical nose, as seen in Fig. 1. The model is placed at the center of a low-speed, open-circuit, wind tunnel where the freestream velocity U_∞ is set to 10 m/s. Measurement of the mean streamwise velocity profile immediately upstream of the separation point exhibits azimuthal uniformity better than 10% of the azimuthal average. The separating boundary-layer Reynolds number based on momentum thickness is 2057; the corresponding Reynolds number based on the step height H is 8700. As reported in Li and Naguib [10], the mean reattachment position x_r is at 4.64H.

Figure 2 shows a schematic drawing of the OHW sensor construction. The sensor is mounted in a wall plug, the top surface of which has a curvature matching that of the surface of the test model downstream of the step. The prongs of the hot wire are attached using epoxy to one end of a piezoelectric beam, and protrude through 0.51 mm-diam holes in an acrylic insert in the wall plug. At the opposite end of the prongs, the piezoelectric beam is rigidly fixed using a clamp made out of phenolic to electrically isolate the piezoelement's electrodes. The OHW sensor is driven to oscillate sinusoidally with/against the flow with an amplitude of a few microns and a frequency of 2.8 kHz. This imposes a high-frequency, small-amplitude sinusoidal signal onto the usual hot-wire output. The wall-shear-stress direction is determined from the phase between this sinusoidal signal and the piezoelement's driving voltage (a 180-deg jump occurs with the change in flow direction), and the magnitude is obtained from the low-pass filtered OHW output, after removal of the imposed oscillation. Because a full oscillation cycle must be completed before the direction is determined, the sampling frequency of the velocity time series is the same as the oscillation frequency. For more details, the reader is referred to Li and Naguib [10].

To extract the wall-shear-stress information from hot-wire measurements, the hot wire is placed very close to the wall (<100 μm), such that the velocity variations in the wall-normal direction may be approximated satisfactorily with a linear function, and the wall shear stress is directly proportional to the measured velocity. The validity of this approximation was checked by repeating the measurements for several sensor heights above the wall to ensure that the results are independent of the hot-wire location (see Li and Naguib [10]).

To calibrate the hot-wire output voltage directly against the wall shear stress, a Couette flow facility was constructed using two parallel discs (one rotating and the other stationary) that are separated by 0.6 mm gap. The facility enabled calibration of the wire in the range of 0–0.7 Pa which encompassed the shear-stress range encountered in the flow. Significant to this method of calibration is

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*Ph.D. Student, Mechanical Engineering Department; currently Caterpillar, Inc.

†Associate Professor, Mechanical Engineering Department, Corresponding author; naguib@egr.msu.edu. Senior Member AIAA.

‡Ph.D. Student, Mechanical Engineering Department; currently General Electric Research.

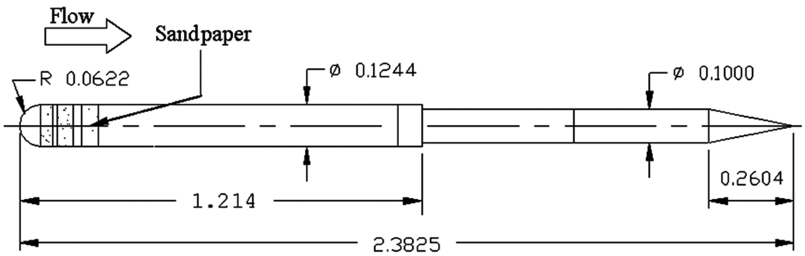

Fig. 1 Schematic drawing of the test model (dimensions in meters).

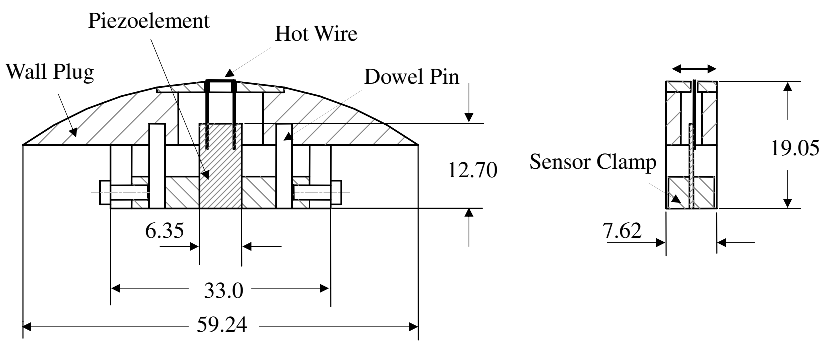

Fig. 2 Drawing of the OHW sensor plug (dimensions in millimeters): end (left) and side (right) views.

the ability to produce very small values of the shear stress and to validate the sensor's directional response by spinning the rotating disc in opposite directions. For all data presented here, calibrations conducted immediately before and after acquisition of the data agreed to within less than 1%. A detailed description of the Couette facility, calibration process, and validation of single-point measurements can be found in Li and Naguib [10].

Two OHW sensors are used in the current study. One sensor (hereafter referred to as the reference sensor) is placed at a fixed position x_{ref} and the other sensor (hereafter termed the movable sensor) is moved along the streamwise x direction. The two sensors are assembled together with spacers to form a wall plug that fits into a matching wall opening downstream of the backstep. The height of the wire above the wall is 97 and 82 μm for the movable and reference sensors, respectively. Both wires are operated in the constant temperature mode with the overheat ratio set to 1.6. The reference sensor location is $5.06H$ downstream of the step ($x_{\text{ref}}/x_r = 1.09$), whereas the movable sensor is placed at 14 different locations extending from the step to $x/x_r = 2.15$. During data acquisition, the movable sensor's location is kept fixed; thus, to compile the entire data set, the experiment is repeated 14 times.

Results and Discussion

The cross correlation $C_{\tau1\tau2}$ of the τ' time series, measured at x_{ref} with the τ' signal recorded by the movable sensor at different locations, is shown using a flooded, gray-level, contour plot in Fig. 3. The abscissa represents the nondimensional streamwise location of the movable sensor (measured from the step) and the ordinate gives the correlation time delay Δt normalized by the freestream velocity and step height. Note that Δt represents the delay of the movable relative to the reference sensor's signal. Also, the correlation value is normalized by the product of the root mean square (rms) of the shear stress at the movable and reference sensors' locations. To enhance the visibility of low-valued correlations, the upper end of the gray-level scale is truncated at 0.5; hence, the contour plot saturates in the neighborhood of the reference sensor location ($x/x_r = 1.09$) and $\Delta t = 0$ where the correlation coefficient has a value near unity. The results in Fig. 3 suggest that the τ' signature is associated with a downstream-traveling disturbance, where the peak correlation shifts toward negative time delay with increasing distance downstream of the step.

Figure 4 (top) shows line plots of $C_{\tau1\tau2}$ results at selected x/x_r locations. For comparison purposes, the wall-pressure cross-correlation coefficient C_{p1p2} at streamwise locations, similar, but not exactly equal, to those of $C_{\tau1\tau2}$, are shown in the bottom part of Fig. 4. The C_{p1p2} results are obtained from wall-pressure-array measurements by Hudy et al. [4] on the same test model and under the same flow conditions. Note that the cross correlation is obtained from the inverse Fourier transform of the cross spectrum. The latter was calculated from an average over 328 and 256 data records, resulting in a random uncertainty of 5.5 and 6.25% for the wall shear stress and pressure, respectively. It is evident that both $C_{\tau1\tau2}$ and C_{p1p2} results reflect the existence of a downstream-traveling disturbance. In fact, the convection speed of this disturbance is practically identical if calculated from the wall-pressure or shear-stress results. This may be seen in Fig. 5, where the time delay Δt_p corresponding to the positive peak of $C_{\tau1\tau2}$ and C_{p1p2} is plotted versus the streamwise location of the movable sensor. The agreement between the Δt_p values obtained from $C_{\tau1\tau2}$ and C_{p1p2} is very good. To obtain the corresponding convection velocity, a least-squares, straight-line fit to the data in Fig. 5 is obtained (shown using a solid line). The inverse slope of this line gives an average convection velocity of $0.48U_\infty$ over the streamwise domain of the measurements. However, Hudy et al. [4]

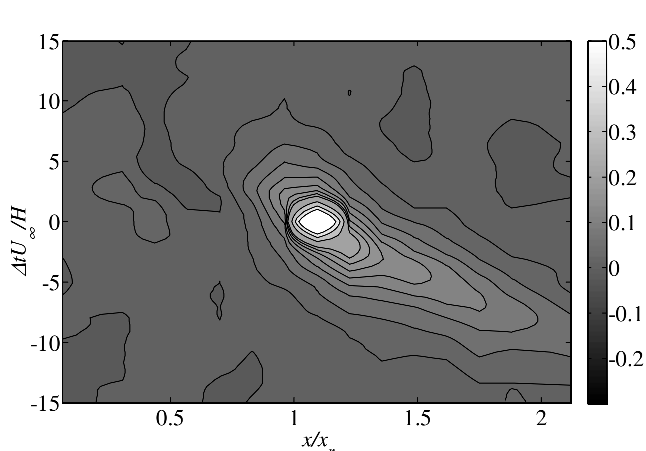

Fig. 3 Contour plot of the two-point, space–time correlation of the wall shear stress (the shaded bar on the right of the plot indicates the contour values).

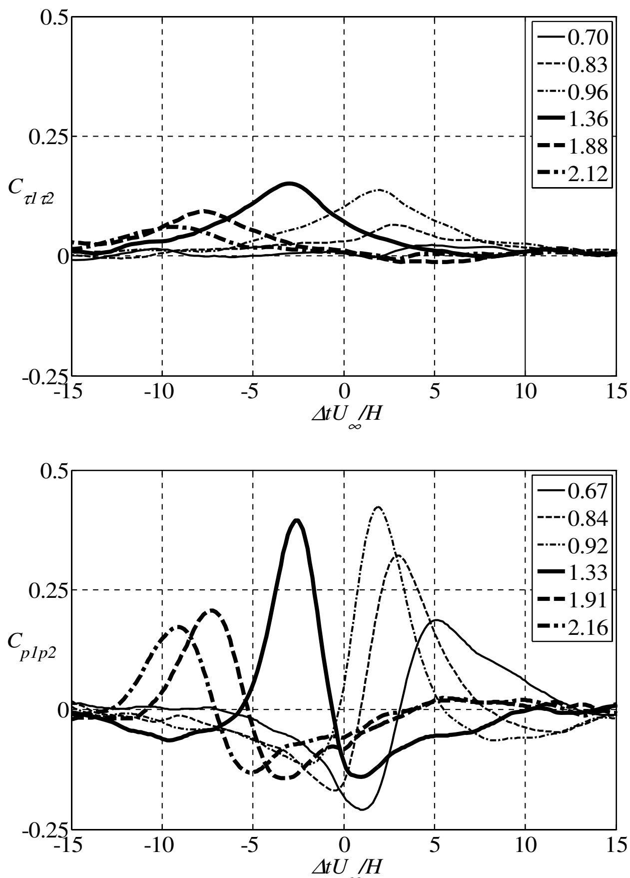

Fig. 4 Comparison between τ' (top) and p' (bottom) correlation results (legend shows x/x_r values). Note that the p' correlations are calculated from data obtained in the study reported in [4].

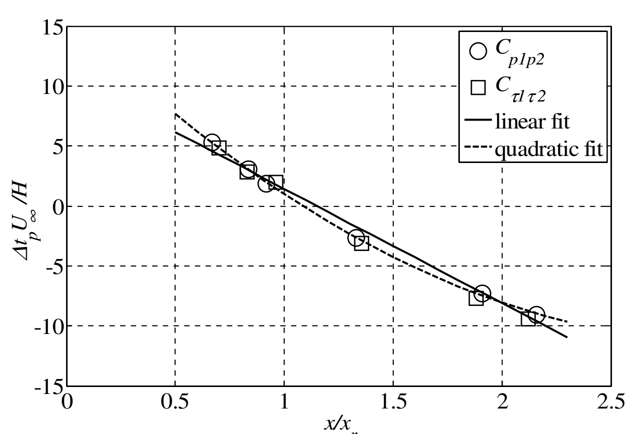

Fig. 5 Comparison between the peak-correlation time delay based on $C_{\tau1\tau2}$ and C_{p1p2}.

showed that a quadratic fit describes the variation of the wall pressure Δt_p with downstream distance more accurately (see broken line in Fig. 5). The quadratic fit implies an increase in the convection velocity with downstream distance, that is, acceleration of the traveling disturbance. From simultaneous particle image velocimetry and wall-pressure measurements, Hudy et al. were able to associate this acceleration with wakelike vortex structures that form, *while stationary in place* at $x/x_r \approx 0.5$, from the roll up of the separating shear layer and subsequently convect downstream. This is also consistent with the results in Fig. 3, where the inclined $C_{\tau1\tau2}$ contours depicting the convective disturbance are only found downstream of $x/x_r = 0.5$.

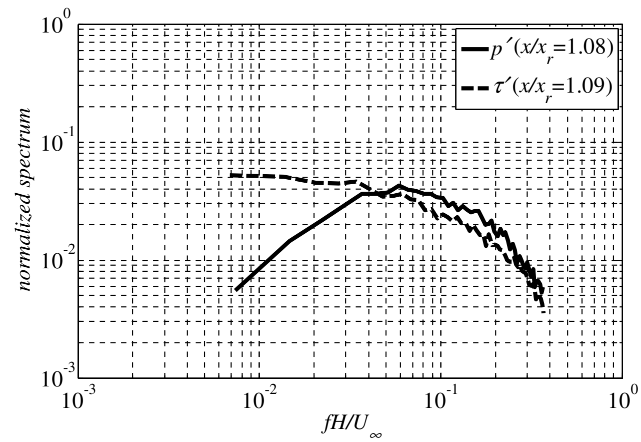

Fig. 6 Comparison between the wall-shear-stress and wall-pressure spectra near reattachment.

Although $C_{\tau1\tau2}$ and C_{p1p2} imply the same convective flow structure, they exhibit some notable differences. In particular, it is clear from Fig. 4 that $C_{\tau1\tau2}$ values are substantially smaller than those of C_{p1p2} at the same x/x_r location. Moreover, $C_{\tau1\tau2}$ curves do not possess a negative correlation peak similar to that seen in the C_{p1p2} results. It is believed that these differences are related to the nature of τ', which is broadband and dominated by low-frequency disturbances, as seen in Fig. 6. The figure depicts a comparison between τ' and p' spectra at the reference sensor location. Note that both spectra are normalized by the corresponding fluctuation energy to compare the plots on the same graph. It is interesting to observe that although the wall-pressure spectrum has a broad peak at $fH/U_\infty \approx 0.06$ (which was shown by Hudy et al. [4] to correspond to the convective structure frequency), the wall-shear-stress spectrum does not show any preferred frequency.

In an attempt to understand the stark difference in the spectrum shape of the wall shear stress and wall pressure, the ideas of Devenport and Sutton [11] are employed. These authors proposed a one-dimensional model in which the near-wall streamwise velocity fluctuation (and hence the associated fluctuating, streamwise wall shear stress) is driven by the fluctuating pressure gradient $(\partial p'/\partial x)$ imposed by the separating shear layer from above. Employing this model, it is straightforward to show (Li [12]) that, at a given frequency, the rms τ' fluctuation is proportional to $(\partial p'/\partial x)/\sqrt{\omega}$ (where $\omega = 2\pi f$ is the angular frequency). The denominator of the latter quantity results from viscous damping, which becomes progressively larger with increasing frequency. Figure 7 provides a comparison between the normalized τ' and $(\partial p'/\partial x)/\sqrt{\omega}$ spectra. The comparison is shown at three different streamwise locations: upstream, near, and downstream of x_r. Although obtained from p' data, qualitatively, the $(\partial p'/\partial x)/\sqrt{\omega}$ spectrum is quite similar to that of the wall shear stress, that is, broadband, dominated by low frequencies, and does not exhibit evidence of the vortex-passing frequency. This suggests that the "smearing" of the vortex-passing signature in the shear-stress spectrum is related to the viscous damping term $\sqrt{\omega}$, which attenuates high frequencies relative to low ones. In turn, this weakens, although does not eliminate altogether, the τ' two-point correlation values associated with the convective flow structure in comparison to their pressure-based counterpart (Fig. 4). Quantitatively, the normalized τ' and $(\partial p'/\partial x)/\sqrt{\omega}$ spectra agree best near the mean reattachment point. Upstream of reattachment, the τ' spectrum decays slower with increasing frequency. Downstream of reattachment, the opposite takes place. Thus, the one-dimensional model of Devenport and Sutton [11] is, strictly speaking, most applicable in the vicinity of the mean reattachment location. Devenport and Sutton provided support for their model using pulsed-wire measurements of the rms streamwise velocity fluctuation. They did not, however, provide spectral information, nor did they have access to surface-pressure measurements under the same flow conditions to provide spectrum-based validation of the model as done here.

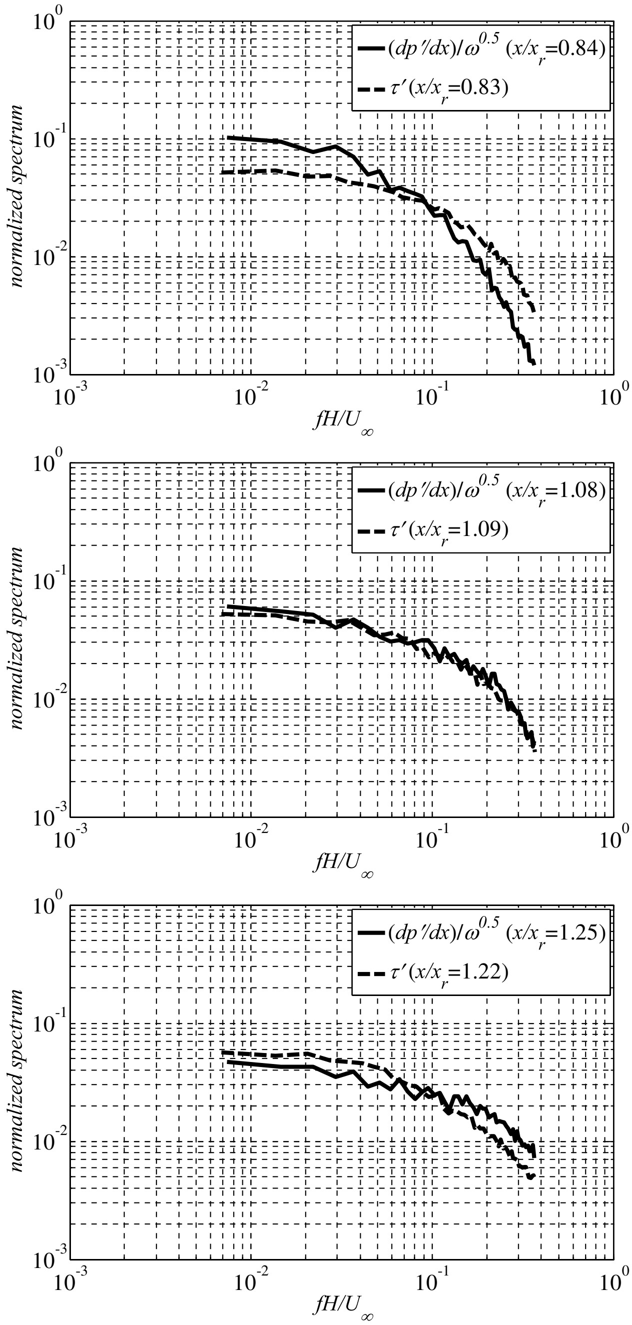

Fig. 7 Comparison between the true and pressure-gradient-derived wall-shear-stress spectra.

Conclusions

The recently developed oscillating hot-wire sensing technique is used to conduct two-point, surface-shear-stress measurements beneath the separation bubble of an axisymmetric, backward-facing-step flow. It is found that, although the wall-shear-stress spectra do not exhibit a peak at the passage frequency of the separating-shear-layer vortices, the signature of the convecting structures is evident in the two-point correlation. The convection speed implied from the latter is in agreement with that obtained from wall-pressure-array measurements in the same flow. By examining the results, in light of the one-dimensional model of Devenport and Sutton [11], the smearing of the vortex-passage frequency in the wall-shear-stress spectra could be linked to viscous damping of higher-frequency, wall-shear-stress fluctuation. Moreover, it is found that Devenport and Sutton's one-dimensional approximation is most accurate in the vicinity of the reattachment point.

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References

[1] Cherry, N. J., Hillier, R., and Latour, M. E. M. P., "Unsteady Measurements in a Separated and Reattaching Flow," *Journal of Fluid Mechanics*, Vol. 144, July 1984, pp. 13–46. doi:10.1017/S002211208400149X

[2] Heenan, A. F., and Morrison, J. F., "Passive Control of Pressure Fluctuations Generated by Separated Flow," *AIAA Journal*, Vol. 36, No. 6, 1998, pp. 1014–1022.

[3] Lee, I., and Sung, H. J., "Characteristics of Wall Pressure Fluctuations in Separated and Reattaching Flows over a Backward-Facing Step, Part 1: Time-Mean Statistics and Cross-Spectral Analyses," *Experiments in Fluids*, Vol. 30, No. 3, 2001, pp. 262–272. doi:10.1007/s003480000172

[4] Hudy, L. M., Naguib, A., and Humphreys, W. M., "Stochastic Estimation of a Separated-Flow Field Using Wall-Pressure-Array Measurements," *Physics of Fluids*, Vol. 19, No. 2, Feb. 2007, pp. 024103. doi:10.1063/1.2472507

[5] Greenblatt, D., Paschal, K. B., Yao, C. S., and Harris, J., "Separation Control CFD Validation Test Case, Part 2: Zero Efflux Oscillatory Blowing," *43rd AIAA Aerospace Sciences Meeting and Exhibit*, AIAA Paper 2005-0485, 2005.

[6] Fernholz, H. H., Janke, G., Schober, M., Wagner, P. M., and Warnack, D., "New Developments and Applications of Skin-Friction Measuring Techniques," *Measurement Science and Technology*, Vol. 7, No. 10, Oct. 1996, pp. 1396–1409. doi:10.1088/0957-0233/7/10/010

[7] Westphal, R. V., Eaton, J. K., and Johnston, J. P., "New Probe for Measurement of Velocity and Wall Shear Stress in Unsteady, Reversing Flow," *Journal of Fluids Engineering*, Vol. 103, Sept. 1981, pp. 478–482.

[8] Spazzini, P. G., Iuso, G., Onorato, M., Zurlo, N., and Cicca, G. M. D., "Unsteady Behavior of Back-Facing Step Flow," *Experiments in Fluids*, Vol. 30, No. 5, May 2001, pp. 551–561. doi:10.1007/s003480000234

[9] Tihon, J., Legrand, J., and Legentilhomme, P., "Near-Wall Investigation of Backward-Facing Step Flows," *Experiments in Fluids*, Vol. 31, No. 5, Nov. 2001, pp. 484–493. doi:10.1007/s003480100300

[10] Li, Y., and Naguib, A. M., "High-Frequency Oscillating-Hot-Wire Sensor for Near-Wall Diagnostics in Separated Flows," *AIAA Journal*, Vol. 43, No. 3, 2005, pp. 520–529. doi:10.2514/1.8264

[11] Devenport, W. J., and Sutton, E. P., "Near-Wall Behavior of Separated and Reattaching Flows," *AIAA Journal*, Vol. 29, No. 1, 1991, pp. 25–31. doi:10.2514/3.10541

[12] Li, Y., "Investigation of the Wall-Shear-Stress Signature in a Backward-Facing-Step Flow Using Oscillating Hot-Wire Sensors," Ph.D. Thesis, Michigan State Univ., East Lansing, MI, May 2004.

N. Chokani
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