A Miniature, Directional Surface-Fence Gage

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Abstract

A NEW, miniature (3.175 mm overall diameter) surface-fence gage was developed to measure simultaneously the magnitude and direction of wall shear stress under three-dimensional turbulent boundary layers. This paper describes the design, calibration, and application of the gage.

Contents

A surface-fence gage has several advantages over a Preston tube or a floating-element gage. Its small size allows for minimum disturbance to the boundary-layer flow. Its calibration is less sensitive to variations from a universal logarithmic velocity profile and is also less sensitive to pressure gradients.[1] Vagt et al.[2] have demonstrated the directional sensitivity of a single surface-fence gage and proposed its use in determining wall shear stress direction by aligning the fence parallel to the local flow direction. A more convenient approach is to extend the dual-gage concept already developed for bidirectional, heat transfer skin-friction gages[3] and to measure the direction and magnitude of wall shear stress simultaneously. The new fence gage has two surface fences placed orthogonal to each other. Such a new gage was fabricated and the results were first reported in Ref. 4. At the same time, Pontikos et al.[5] independently reported the development of a probe similar in design but significantly larger in overall diameter. For measurements of the mean wall shear stress the present fence gage proved to be more convenient and stable than a heat transfer skin-friction gage. Since it is an integral unit, the fence gage does not require a separate run to measure the static pressure as required by the razor-blade[6] or the obstacle-block techniques.[7]

The top and cross-sectional views of the directional surface-fence skin-friction gage are shown in Fig. 1. The overall diameter of the gage is 3.175 mm, mounted on the end of a 38-mm-long cylinder for easy installation on the model. Each fence is machined out of a brass end plug to have a tapered cross section as shown. (Another gage with untapered fences gave similar calibration results, the differences being attributable to the fence heights.) Four pressure taps were placed immediately in front of and behind each of the fences by an electrical discharge machining technique. The end of each pressure tap is connected to a 1.59-mm stainless steel tube for measurements by electronic pressure transducers.

The gage was calibrated for both magnitude and directional sensitivities at various probe orientations and freestream velocities ranging from 10 to 83 m/s under two-dimensional and axisymmetric turbulent boundary layers in low-speed atmospheric wind tunnels. In addition to the measured mean velocity profiles, a Preston tube of 1.07-mm outer diameter was used as a standard to obtain the skin friction under these two-dimensional turbulent boundary layers.

The determined calibration equation is

$$Y^* = 0.6727X^* - 0.5491 \qquad \text{in the range } X^* < 3.0 \qquad (1)$$

where $Y^* = \log_{10}[\tau_w h^2/4\rho\nu^2]$ and $X^* = \log_{10}[\Delta P_{\text{normal}} h^2/4\rho\nu^2]$; τ_w is the magnitude of the wall shear stress; h the fence height; ρ and ν the density and kinematic viscosity of air, and ΔP_{normal} the pressure difference across the fence placed normal to the direction of the wall shear stress. In this range, the response of each individual element closely matches Patel's calibration of a surface fence ($\Delta P \approx \tau_w^{1.5}$).[1] Y^* is related to the Reynolds number based on the shear velocity as

$$h^+ = (u_\tau h/\nu) = 10^{(Y^*/2 + \log 2)}$$

Thus this region corresponds to $h^+ < 10$. In the range $X^* > 3.0$, however, the pressure difference becomes less sensitive to a change of wall shear stress and the slope is somewhat closer to $\Delta P \approx \tau_w^{1.35}$. Thus, the application limit of the calibration is $h^+ < 10$.

The directional sensitivity of each fence is shown in Fig. 2. The data have been normalized with those of the fence normal to the local flow. A general characteristic of the curve indicates the following relationships:

$$\Delta P_L = F_L(\tau_w) \cdot G_L(\alpha_L) \doteq \Delta P_{\text{normal}}(\tau_w) \cdot G(\beta - 45\,\text{deg}) \qquad (2a)$$

$$\Delta P_R = F_R(\tau_w) \cdot G_R(\alpha_R) \doteq \Delta P_{\text{normal}}(\tau_w) \cdot G(\beta + 45\,\text{deg}) \qquad (2b)$$

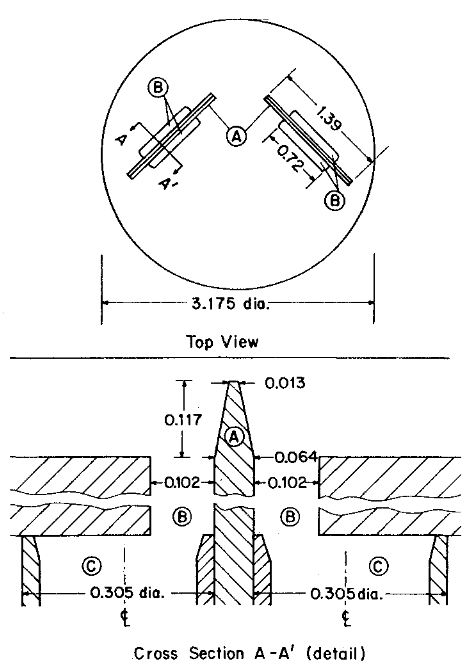

Fig. 1 Top and cross sectional views of the directional surface fence gage. A: fence elements, B: presssure taps, C: stainless steel tubings. Dimensions are in millimeters.

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where subscripts L and R designate individual fence elements on the gage, F and G the magnitude and directional sensitivities, β the direction of the wall shear stress with respect to the gage centerline, and α_L and α_R those with respect to each fence. Note the output $\Delta P \approx 0$ when the fence is oriented parallel to the local flow ($\beta = \pm 45$ deg). If Eqs. (2a) and (2b) hold, the following function then depends only on the direction of the skin friction:

$$(\Delta P_L - \Delta P_R)/(\Delta P_L + \Delta P_R) = H(\beta) \tag{3}$$

The calibration data are presented in Fig. 3, and their self-similarity is evident. Scatter in data at yaw angles larger than 50 deg is caused by the wake of an upstream fence. When the fences are rotated further to be clear of each other's wake, the calibration curve resembles that of the front side of the probe. This useful feature of the probe can be applied in the presence of reverse flow regions without having to realign the probe.

The accuracy in the directional sensitivity of the present gage was better than ± 2 deg independent of the magnitude of the shear stress. Accuracy in the magnitude of the shear stress was estimated to be within $\pm 5\%$. These uncertainties are due partly to the inaccurate installations of the fence gage to be flush with the test surface, and partly to the inherent limitations of a Preston tube and static-pressure tap combination used as a standard.

Once the gage is calibrated, a measurement within an unknown, three-dimensional boundary layer can be made using Figs. 3 and 2 and Eq. (1). First, the pressure differences ΔP_L and ΔP_R are recorded across both fences and from Fig. 3, and

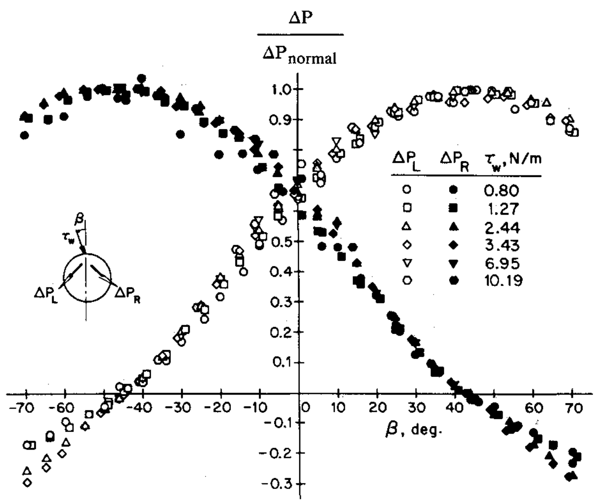

Fig. 2 Directional sensitivities of individual fence elements.

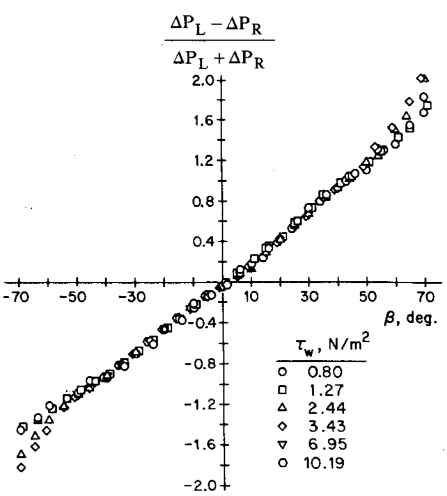

Fig. 3 Directional calibration of the surface-fence gage.

the direction of the wall shear stress, β, is determined. Next, ΔP_{normal}, which is the pressure difference across the fence as if each fence had been normal to the local shear stress direction, is obtained from Fig. 2. Finally, from Eq. (1), the magnitude of the wall shear stress is determined. The value of h^+ (the extent of the viscous sublayer relative to fence height) should be within the valid calibration range in order to minimize the effect of the pressure gradient and possible near-wall turning within the fence heights.

This directional, surface-fence gage was used to measure the magnitude and direction of wall shear stress under a swirling turbulent boundary layer subjected to a sudden change in the transverse strain. Details of the experiment and its results are discussed in Ref. 4.

Concurrent with the development of the present gage, Monson et al.[8] utilized a laser interferometer to measure the wall shear stress by monitoring a thickness variation of a thin oil film well within the viscous sublayer. This interferometer method was applied to the current three-dimensional boundary layer.[9] The agreement among all the methods used was excellent.[10]

The small size of the present gage enabled an application on a curved surface without any appreciable mismatch with the model contour. It is also worth mentioning that shear-driven, three-dimensional boundary layers, for which the probe was originally designed, presented a somewhat favorable environment because the near-wall velocity profile was collateral beyond the fence height, i.e., there was no significant turning of the flow direction in the immediate vicinity of the wall (see Fig. 10 in Ref. 4). In other types of three-dimensional turbulent boundary layers, where the cross flow is generated by a transverse pressure gradient, a considerable near-wall flow turning is suspected to exist such that there can be an averaging of the flow direction across the fence height. However, as verified within a three-dimensional separating boundary layer at the base of an airfoil placed normal to the wall,[10] the turning within the fence height was concluded to be negligible under a normal operating condition.

Acknowledgments

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