In turbulent boundary layers, the flow structures responsible for high skin-friction are the randomly distributed high-speed streaks that have transverse length scales of hundreds of microns and life spans on the order of milliseconds (or less). The availability of MEMS technology that is capable of producing transducers matching the length and time scales of the streaks have made possible the development of an adaptive control system that deals with each individual streak for surface shear-stress reduction.

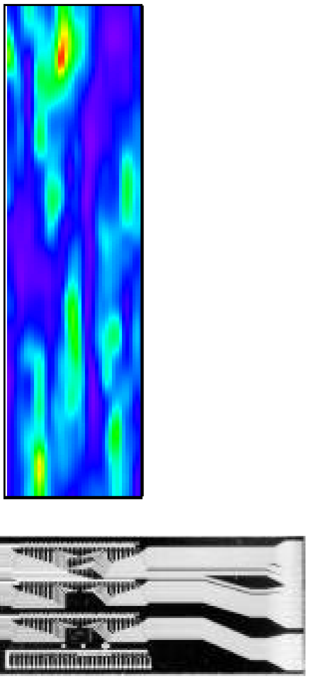

Figure 1: Shear-stress imaging chip and typical instantaneous surface shear stress measurement

In order to apply control, two components are necessary. The first is a sensor that is capable of resolving the shear stress streaks. The second is an actuator that can apply localized control. A micro shear-stress sensor has been developed specifically to measure the local surface shear stress in a turbulent channel-flow wind tunnel. The sensor measures the shear-stress based on heat transfer from a micro heating element. 85 of these sensors, arranged in 3 arrays of 25 sensors covering a spanwise length of 7.5 mm and 2 arrays of 5 sensors, were implemented onto an imaging chip, which allows for the measurement of the instantaneous turbulent shear-stress distribution. A constant temperature circuit drives each sensor. The imaging chip and a typical instantaneous surface shear-stress contour is shown in Figure 1. Comparisons of the turbulent statistics as measured by these sensors and previous experimental results have shown good agreement. Two different types of actuators have been developed to apply the control. One is a silicon micro-flap actuator, driven magnetically. The other is a bubble actuator, driven pneumatically. The micro-flap actuator and a strip type bubble actuator are shown in Figure 2. Extensive studies have been done in the case of the micro-flap actuator. Studies with bubble actuators are ongoing.

Figure 2: Micro-flap and bubble actuator

The first step in the control process is the identification of a shear-stress streak. The identification procedure must be able to recognize the presence of a streak and separate it from the background fluctuations. This must also be performed in a rapid manner to allow enough time to activate the actuator. This is achieved by setting a threshold limit whereby any stress values above this limit will be recognized as a shear-stress streak. Statistical analysis of experimental data have also shown that the initial stress gradient of a shear-stress streak has a correlation with the peak stress value within that streak which is a function of the Reynolds number. The importance of this knowledge will be explained.

Extensive actuator studies have been performed with a 4 mm by 4 mm micro-flap actuator. A 1.3 mm thick vortex generator was used to generate a longitudinal vortex pair in a laminar boundary layer. The vortices convect high-speed fluid to the wall, inducing a local high shear-stress streak on the surface. The actuator was placed downstream of the vortex generator where the vortex paired was generated. As the actuator oscillates, it generates perturbations in the flow which change the shear-stress intensity of the streak. Experiments were carried out for different combinations of actuator frequency (ω) and maximum tip height (d).

To evaluate the effects of the actuator oscillation, the net drag coefficient, C_{DN}, defined as,

$$C_D(\theta) = \frac{1}{0.5\rho U^2}\int_{-Z}^{+Z} \mu \frac{\partial u}{\partial y}, \text{ and}$$

$$C_{DN} = \int_0^{2\pi} [C_D(\theta) - C_{D,VG}]\, d\theta\ ,$$

was evaluated. The results for different combinations of ω and d are shown in Figure 3. It was found that a higher drag reduction is achieved at a higher ω and higher d. Furthermore, it was also found that for a constant ωd, similar drag reduction is achieved, indicating that the product of d and ω is an important control parameter. It is desirable that the flap be operated at the minimum "d" in order to minimize form drag. Thus, by knowing the peak stress value within a streak, "d" can be determined for the best probably shear-stress reduction. Ongoing work includes implementing a control scheme as developed by J. Kim et al to control an array of actuators. The final objective is to integrate the sensor, control circuitry, and actuator onto a single chip.

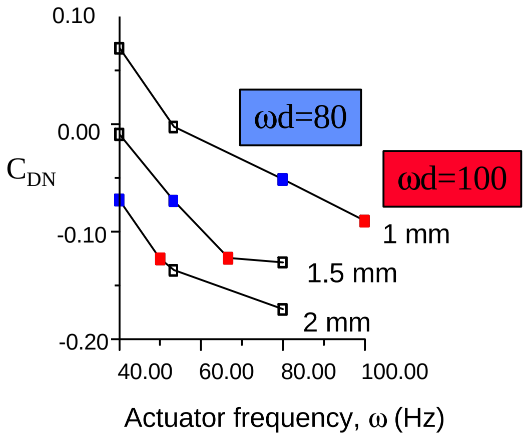

Figure 3: Drag coefficient vs. actuation frequency