Experimental Studies to Reveal the Boundary Layer Control
Mechanisms of Shark Skin

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Introduction
It is hypothesized that loosely attached shark scales (such as found on shortfin mako) are used to control boundary layer separation thereby reducing drag and increasing turning ability.

We theorize that the scales utilize three mechanisms in reducing the likelihood of boundary layer separation:
1. Create a preferential flow direction
2. Create a partial slip condition
3. Induce turbulence augmentation

Mechanism 1: Preferential Flow Direction
- All of the scales are aligned in the direction of the flow over the shark’s body. This causes a reversing flow to bristle the scales and trap flow between them, creating embedded vortices between the scales.
- The riblets, or streamwise grooves, on top of the scales help channel the flow beneath the upstream scale as flow reversal is beginning to occur.
- Also, the grooves on all the scales work together, even when not bristled, to encourage a generic streamwise flow direction, which prevents crosswise flow. This keeps the flow approximately two-dimensional in the vicinity of the surface. Riblets are also known to reduce turbulent skin friction drag.

Mechanism 2: Partial Slip Condition
- As the boundary layer begins to separate, fluid begins to flow backwards near the surface (red arrows above). This fluid flows down into the cavities between scales, causing them to bristle, and also forming vortices between the scales.
- These vortices interact with the flow at the surface, just above the bristled scales, and create a partial-slip condition, resulting in a flow velocity at the surface that is no longer zero but some percentage of the freestream flow.
- This velocity at the surface prevents global flow reversal and allows the boundary layer to remain attached.

Mechanism 3: Turbulence Augmentation
- The cavities present in the skin interacting with a turbulent boundary layer aid to mix high momentum flow towards the surface.
- This helps to energize the cavity vortices thereby increasing the partial slip velocities and also brings high momentum flow down to both these effects deter flow separation.

Experiments and Results
- We use DPIV to observe and measure the mechanisms at work.
- To observe the vortices forming within the cavities, bristled shark skin models are’applying.

Conclusions & Future Work
- The shark skin appears to have a passive flow-actuated mechanism which consists of localized scale bristling leading to the formation of an embedded vortex structure. This inhibits flow reversal and the further development of global flow separation.
- Future models will vary the angle of bristling to better match new observations made by biologists.
- In summer 2011 actual shark skin specimens will be tested for the first time. 

Background
- Fast-swimming sharks have an array of hard scales (denticles) that sit above the skin and can be loosely or strongly embedded depending on the body location. Crown length of a single scale measures approximately 200 µm.
- Recent results suggest angles of bristling in excess of 30º are effective at reducing downstream drag.

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Figure 1: Schematic of the terminal boundary layer structure near the point of separation (Cassel et al., 1996).

Figure 2: Histology of shortfin mako shark skin. Scales on back behind dorsal fin are firmly embedded (left) while scales on sides of body are loosely embedded due to a smaller base (right). Images from Dr. Phil Motta.

Figure 3: Scales on a hammerhead shark looking down on top. Scales laying flat (left) and scales bristled using sandpaper and allowed to dry in place (right). Images from Dr. Phil Motta.

Figure 4: Bristled shark skin model. (A) Pro-E rendering. (B) Model built for water tunnel testing with shark skin embedded into the flat plate model.

Figure 5: (Left) Flow visualization showing embedded vortex formation in a bristled shark skin model. (Right) DPV measuring vortex inside model. Laminar boundary layer encountering model in both cases.

Figure 6: (Left) DPIV showing vortex at 20% cavity depth under laminar conditions. (Right) Re-constructed vorticity field induced by shark skin cavity geometry.