Active Control of Transition Using the Lorentz Force

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Abstract

A new concept and technique has been developed to directly control boundary-layer transition and turbulence. Near-wall vertical motions are directly suppressed through the application of a Lorentz force. Current (j) and magnetic (B) fields are applied parallel to the boundary and normal to each other to produce a Lorentz force ($j \times B$) normal to the boundary. This approach is called magnetic turbulence control (MTC). Experiments have been performed on flat-plate transitional and turbulent boundary layers in water seeded with a weak electrolyte, at $Re_\theta \simeq 1700$. With the application of modest field densities (eg. $|B| < 1{,}000$ gauss and $|j| < 10$ mA/cm^2), measured reductions in mean and fluctuating turbulent stresses within the control region are seen to exceed 90%. Laser-sheet flow visualization confirms the substantial reductions in turbulent motion at $y^+ \lesssim 15$. The talk will present some theoretical considerations and initial experimental findings. Experiments with arrays of MTC 'tiles' will also be discussed.

Princeton University

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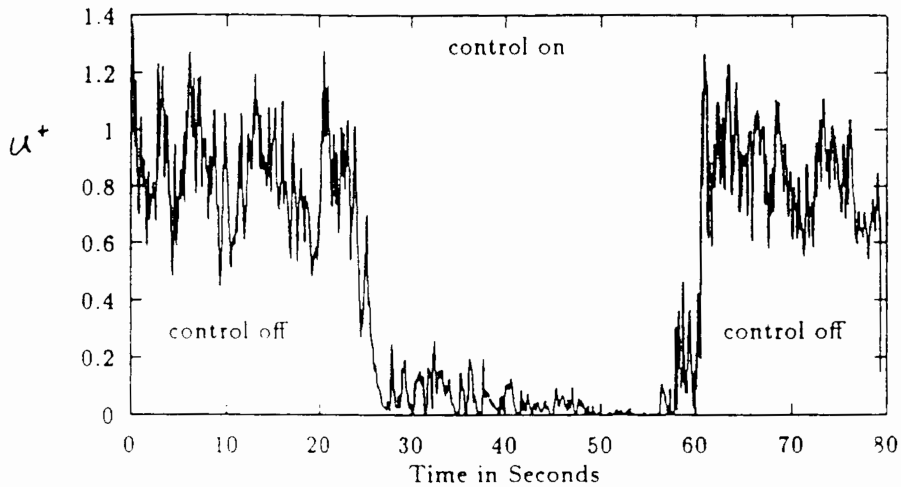
Department of
Mechanical and
Aerospace Engineering

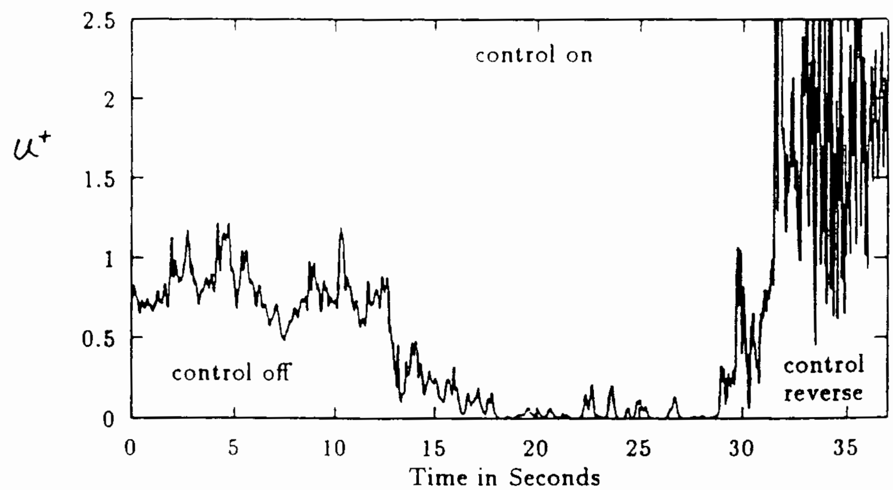
Control of Transition and Turbulence

- The end-stage of transition and turbulence are characterized by:
  - periodic eruptions of unstable, low-momentum 'near-wall' fluid
  - subsequent inrush of high-speed 'outer-flow' fluid
  - resultant large skin-friction drag
- Lorentz force easily generated:
  - surface electrodes produce electric field with current density j
  - magnetic field B is generated parallel to surface and normal to electric field
  - resultant normal force is $j \times B$
- Direct application of wall-normal force could prohibit lift-up and bursting of near-wall fluid
- Exploit three-dimensional Lorentz force in fluids of uniform conductivity

Key Results



a: Control Sequence: Off-On-Off



b: Control Sequence: Off-On-Reverse

MTC on Centerline at $y^+ \sim 1$
Velocity vs Time

Theoretical Considerations

- MOMENTUM

$$\rho \frac{D\mathbf{u}}{Dt} = -\nabla p + \mathbf{L} + \mu \nabla^2 \mathbf{u}$$

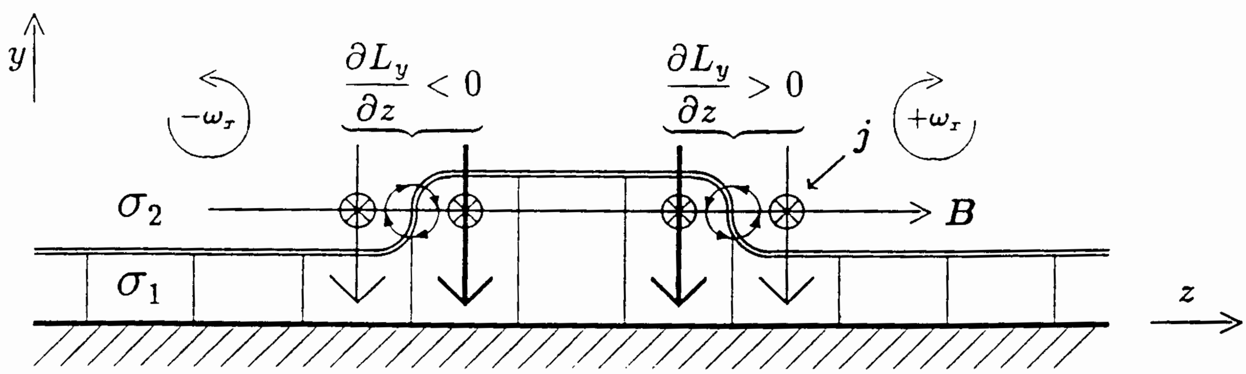
where $\mathbf{L} = \mathbf{j} \times \mathbf{B}$ (Lorentz force)

- VORTICITY

$$\rho \frac{D\omega}{Dt} = \rho\omega \cdot \nabla\mathbf{u} + \nabla \times \mathbf{L} + \mu \nabla^2 \omega$$

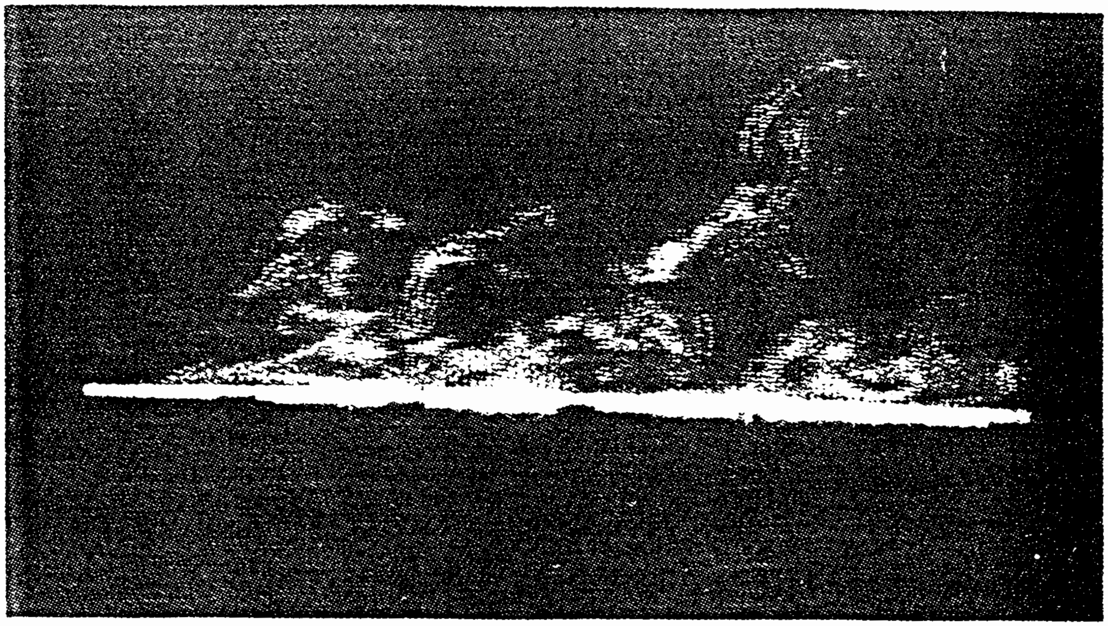
If $\mathbf{L} = L_y e_j$:

$$\rho \frac{D\omega_x}{Dt} = \rho\omega \cdot \nabla\mathbf{u} - \frac{\partial L_y}{\partial z} + \mu \nabla^2 \omega_x$$

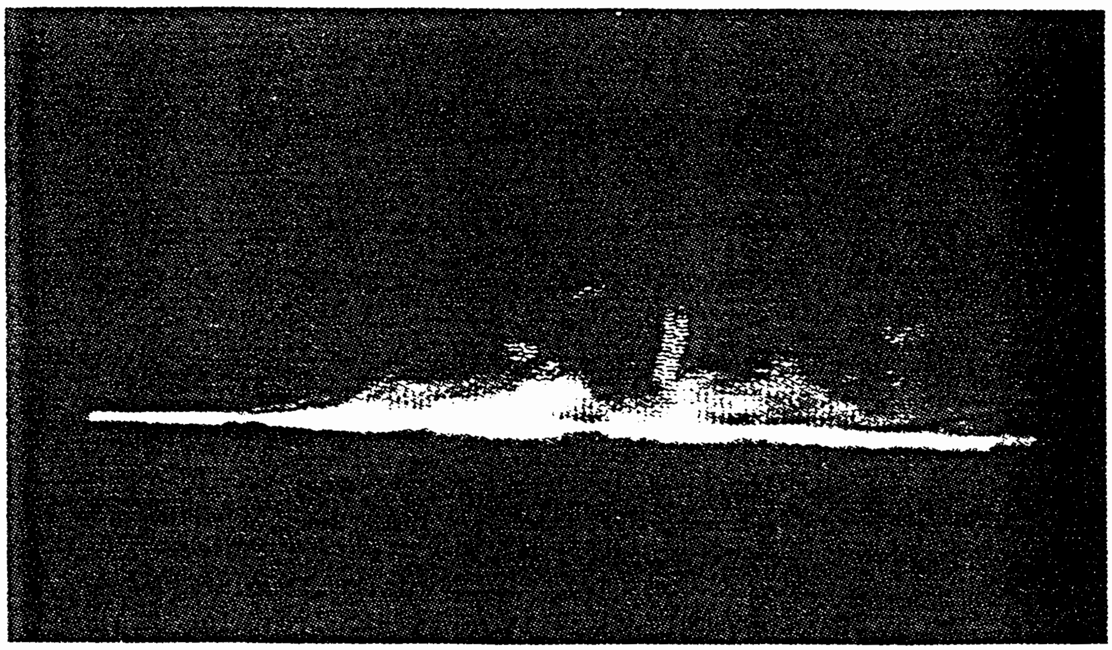


- Conductivity Gradient Controls Stability

$$\frac{\partial L_y}{\partial z} \approx \frac{\partial}{\partial z}\sigma e_z B_x \approx e_z B_x \frac{\partial \sigma}{\partial y}\frac{\partial y}{\partial z}$$



Control Off



Control On

MTC Control of Turbulent Spots

NaOH throughout Boundary Layer

($\emptyset_1$, $\emptyset_2$, $\emptyset_3$ Active)

TILING

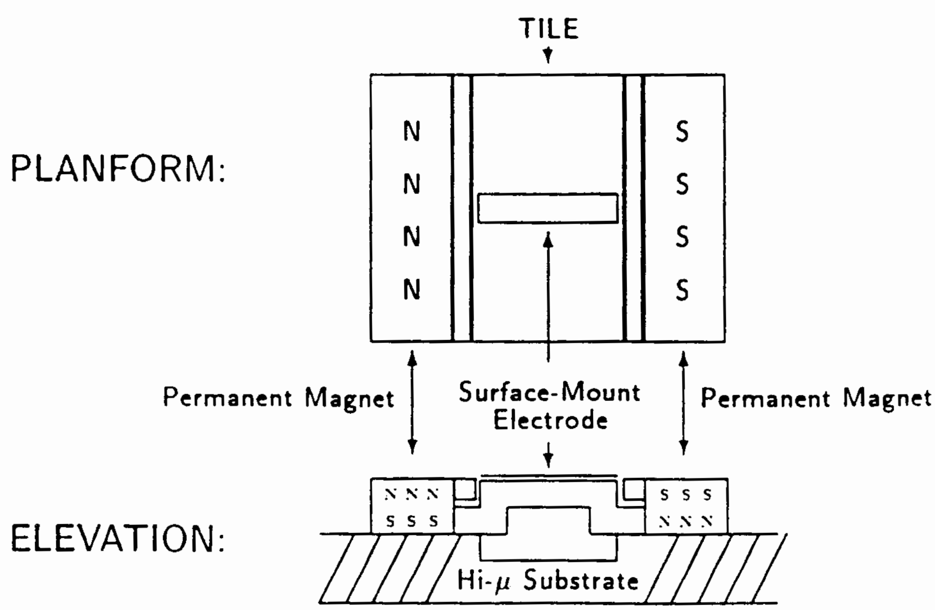
- Concentrate Lorentz force in near-wall region

- Large area coverage requires 'tiles'

- A TFM (turbulent flow modulation) tile is defined as that region on the wall bounded by two electrodes and two magnet poles

- Globally-uniform electric field established by phased operation and alternating electrode polarities

- Tile arrays formed with modular building blocks:



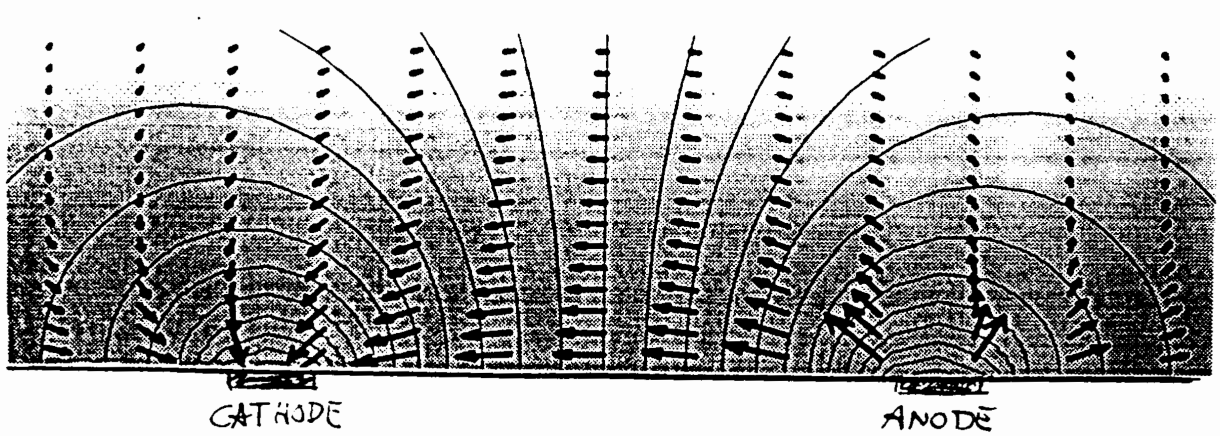
Three-Dimensional Theoretical Considerations

- VORTICITY

$$\rho\left[\frac{\partial\omega_i}{dt}+\frac{\partial}{\partial x_k}\left(u_k\omega_i-\omega_k u_i-\nu\frac{\partial\omega_i}{dx_k}\right)\right] \;=\; \epsilon_{ijk}\frac{\partial L_i}{\partial x_k}$$

  where $\epsilon_{ijk}\frac{\partial L_i}{\partial x_k}$ may be viewed as a vorticity source term

- Three-dimensional TFM electric and magnetic field lines can produce a Lorentz force-field that generates vorticity to 'capture' near-wall fluid



Grey-level indicates B-field strength
Contours indicate electric-field potential
Arrows denote current density j.