Controlling the Onset of Turbulence by Downstream Traveling Waves

The global energy crisis has increased awareness of the need for renewable energy generation and more efficient transportation means. This motivates research and development of cost-effective wind and tidal energy harvesting as well as fuel-efficient and environmentally friendly vehicles. Understanding and controlling fluid flows plays an important role in all of these applications, and may therefore have critical effects on our economy and environment.

Fluid motion is classified as either laminar or turbulent; flows that are smooth and ordered, laminar, may become complex and disordered, turbulent, as the flow speed increases. This process is known as transition to turbulence. Turbulent flow around cars, airplanes, and ships increases resistance to their motion (drag). For example, about half of the fuel required to maintain the aircraft at cruise conditions is used to overcome the drag force imposed by the turbulent flow. Similarly, in wind farms, turbulence reduces the aerodynamic efficiency of the blades, thereby decreasing the energy capture. In the absence of atmospheric disturbances, flow around an aerodynamically perfect aircraft wing or wind turbine would remain laminar all the way from the leading edge to the rear. However, disturbances and design imperfections may trigger turbulence (Figure 1). Current practice combines physical intuition with costly numerical simulations and experiments in an attempt to mitigate transition to turbulence. Even though simulations and experiments offer valuable insights into the performance of control strategies, their effectiveness can be significantly enhanced by flow control design based on analytical models and optimization tools.

The research team from the De-

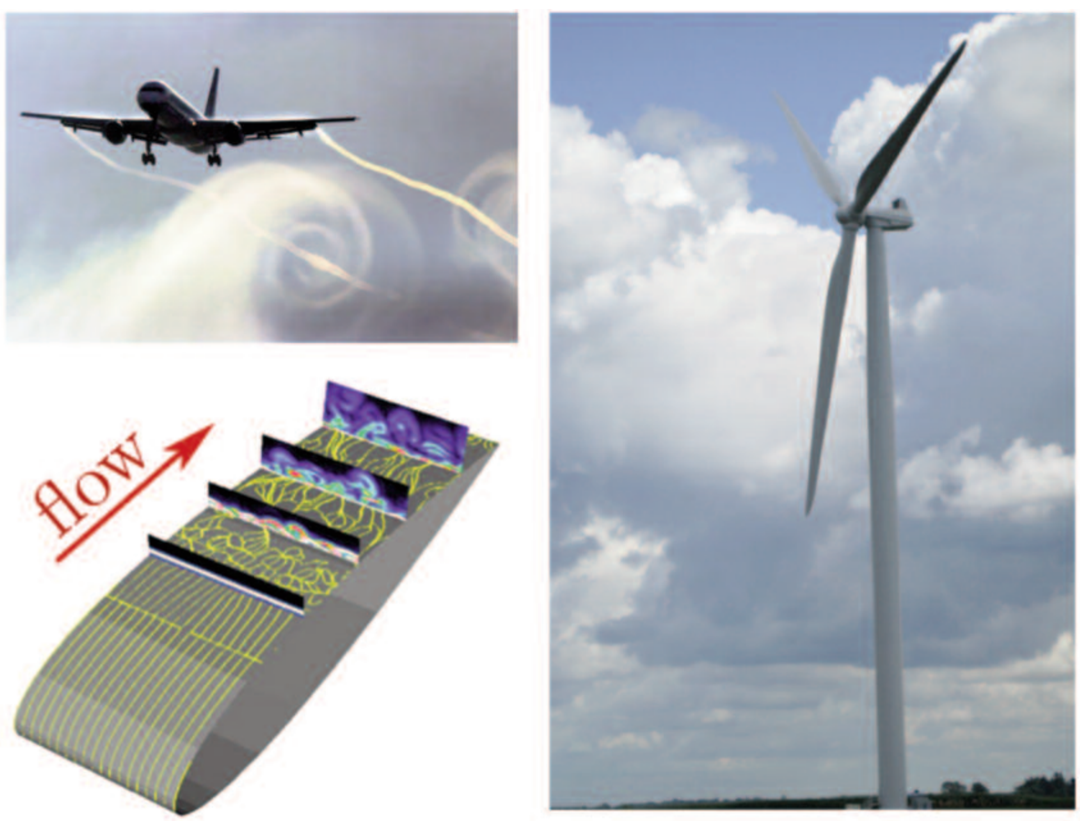

Figure 1. Ordered (laminar) flow around an aircraft wing, or a wind turbine blade, becomes complex and disordered (turbulent) as it moves away from the leading edge. E-fluids photo (bottom left) by Miguel Visbal.

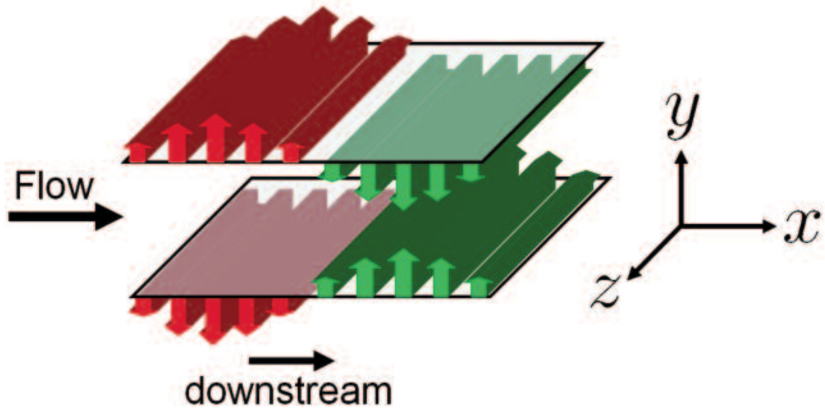

Figure 2. Channel flow with blowing and suction along the walls. Channel flow is commonly used as a benchmark for turbulence suppression studies. In the absence of control, air flows in the downstream direction between two parallel walls. Through wall perforations, control injects (green arrows) and takes out (red arrows) a small quantity of air without introducing additional mass. The actuation is characterized by three design parameters: amplitude, frequency, and speed of the traveling wave.

partment of Electrical and Computer Engineering, led by Professor Mihailo Jovanovic, has developed theory and techniques for sensor-less flow control in order to prevent transition to turbulence. Parallel attempts to control turbulence via surface-mounted arrays of sensors and actuators are often prohibitively expensive as they call for rather sophisticated control mechanisms and information processing. Instead, sensor-less flow control represents a viable and effective alternative with many advantages. Inspiration for this type of control often comes from nature. For example, the skin of sharks is textured with micro-grooves which help them swim with reduced friction. This observation has inspired the development of sharkskin-like surface coatings for drag reduction in vehicles.

In recent *Journal of Fluid Mechanics* papers (vol. 663, November 2010), doctoral students Rashad Moarref and Binh Lieu, together with Professor Jovanovic, have pioneered a model-based approach to sensor-less flow control, where the dynamics are impacted by zero-mean oscillations. Their methodology avoids the need for expensive numerical simulations and experiments at the early stages of control design. It also facilitates synthesis of superior turbulence suppression strategies compared to what was earlier thought possible.

The methodology has been applied to study the onset of turbulence in a channel flow subject to surface actuation in the form of downstream traveling waves (Figure 2). This study disentangles three distinct effects of blowing and suction on (i) resistance to motion; (ii) cost of control; and (iii) kinetic energy reduction. For small amplitude actuation, a weakly nonlinear analysis was utilized to determine how base-flow is affected, and to assess the resulting cost of control. Sensitivity analysis of the velocity fluctuations around this base-flow was then employed to design the traveling waves. This simulation-free approach reveals that, relative to the flow with no control, the downstream waves with properly designed speed and frequency can significantly reduce high flow sensitivity, making them well-suited for controlling the onset of turbulence. In contrast, the upstream waves increase sensitivity of the velocity fluctuations to disturbances and, consequently, promote turbulence. The theoretical predictions, obtained by perturbation analysis of the linearized flow equations, have been verified using high-fidelity simulations of the nonlinear flow dynamics. These were conducted using MSI's supercomputing resources and they showed that a positive net efficiency as large as 25% relative to the uncontrolled turbulent flow can be achieved with downstream waves. Furthermore, it was shown that these waves can even re-laminarize turbulent flows. This work has demonstrated that the theory developed for the linearized flow equations with uncertainty has considerable ability to predict full-scale phenomena, and that transition can be inhibited by reducing the tremendous sensitivity of flow dynamics using either active or passive means.

Formulation of the control objective was motivated by recent research showing that high flow sensitivity to disturbances and design imperfections triggers transition to turbulence. For example, surface roughness and free-stream turbulence can introduce departure from laminar flow. The effect of downstream traveling waves on sensitivity is quantified by the energy

$$\text{Equation 1:} \quad \text{energy amplification} = \frac{\text{energy of flow with control}}{\text{energy of flow without control}}$$

$$= 1 + (\text{wave amplitude})^2 \times g$$

of velocity fluctuations in stochastically forced flows. For small amplitude actuation, perturbation analysis provided an explicit formula for energy amplification, shown above in Equation 1.

This formula was used to identify the wave frequencies and speeds that reduce flow sensitivity. The plot of the function "g" in Figure 3 reveals the wave parameters that amplify (red regions) or attenuate (blue regions) the most energetic modes of the flow with no control. Further analysis has confirmed that the energy amplification trends are captured by the second order correction in the wave amplitude. Most notably, all theoretical predictions have been verified using full-scale numerical simulations of the nonlinear flow dynamics (Figure 4, page 7).

The contribution of this work goes beyond the problem of designing transpiration-induced downstream traveling waves. The developed theory and techniques may also find use in designing periodic geometries and waveforms for maintaining the laminar flow or drag reduction in vehicles or wind turbines. This work suggests that reducing high flow sensitivity represents a viable approach for controlling the onset of turbulence. It also offers a computationally attractive method for determining the energy amplification of flows subject to periodic controls.

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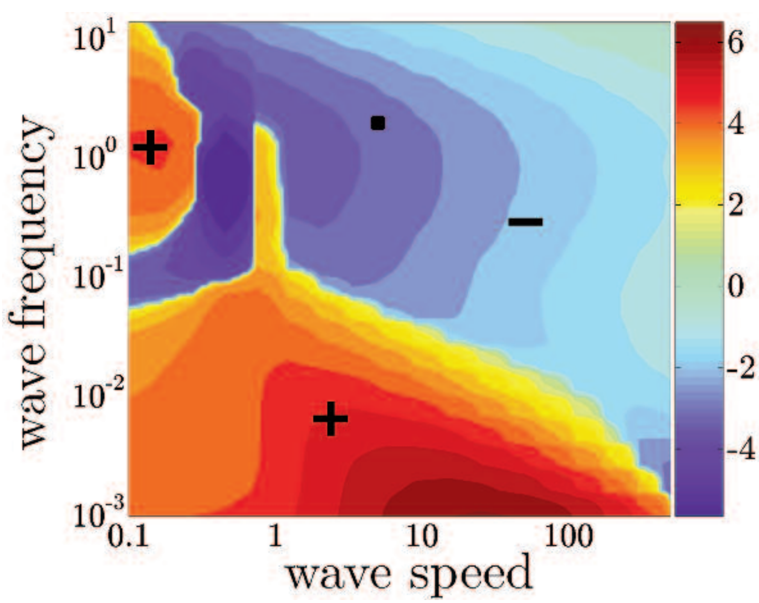

Figure 3. Influence of small amplitude downstream waves on the most energetic modes of the flow with no control is determined by the sign of the function "g". The Reynolds number (i.e., the ratio of inertial to viscous forces) is set to 2000. The plot is colored using a sign-preserving logarithmic scale. Up to second order in the wave amplitude, the speed and frequency associated with the blue regions reduce the energy amplification. The black square denotes the control parameters that provide a good balance between sensitivity reduction and low cost of control.

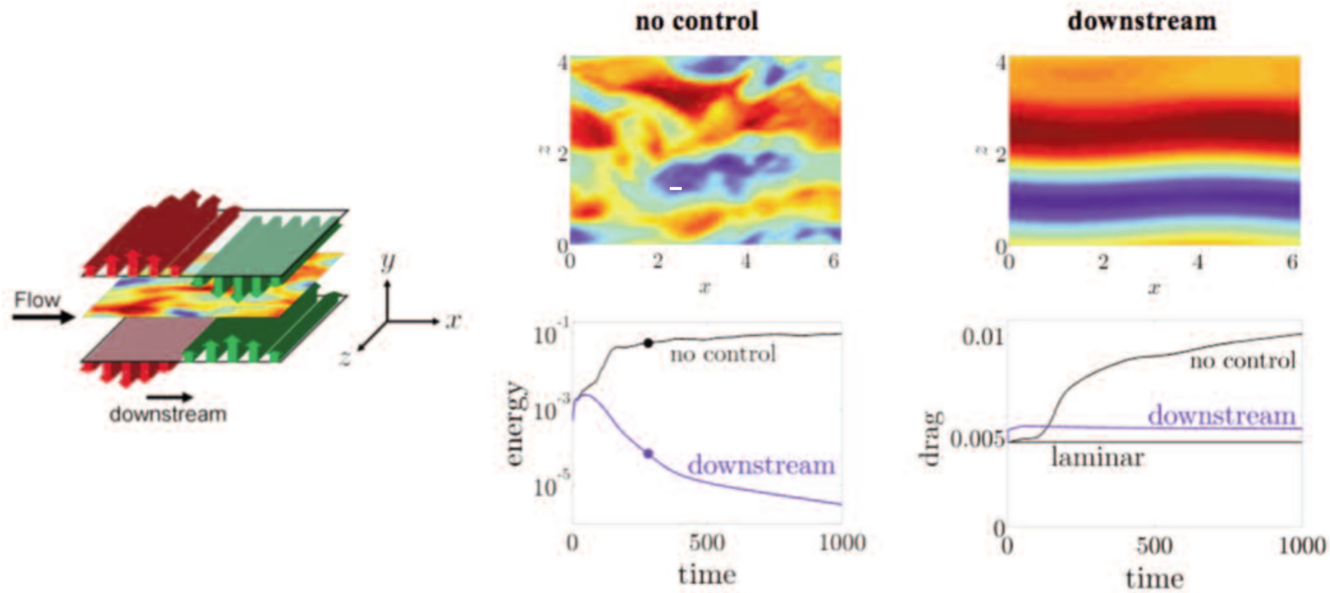

Figure 4. Top row: the stream-wise velocity fluctuations at the channel's center-plane for the flows with and without control. The uncontrolled flow fluctuations are disordered with a broad range of spatial and temporal scales, and in the controlled flow they are smooth and ordered. Bottom left: the fluctuations' kinetic energy as a function of time. The downstream waves prevent the flow from becoming turbulent by suppressing growth of energy, while the uncontrolled flow triggers turbulence by promoting growth of energy. Bottom right: the drag coefficient as a function of time. The controlled flow has about 50% less drag than the uncontrolled flow.

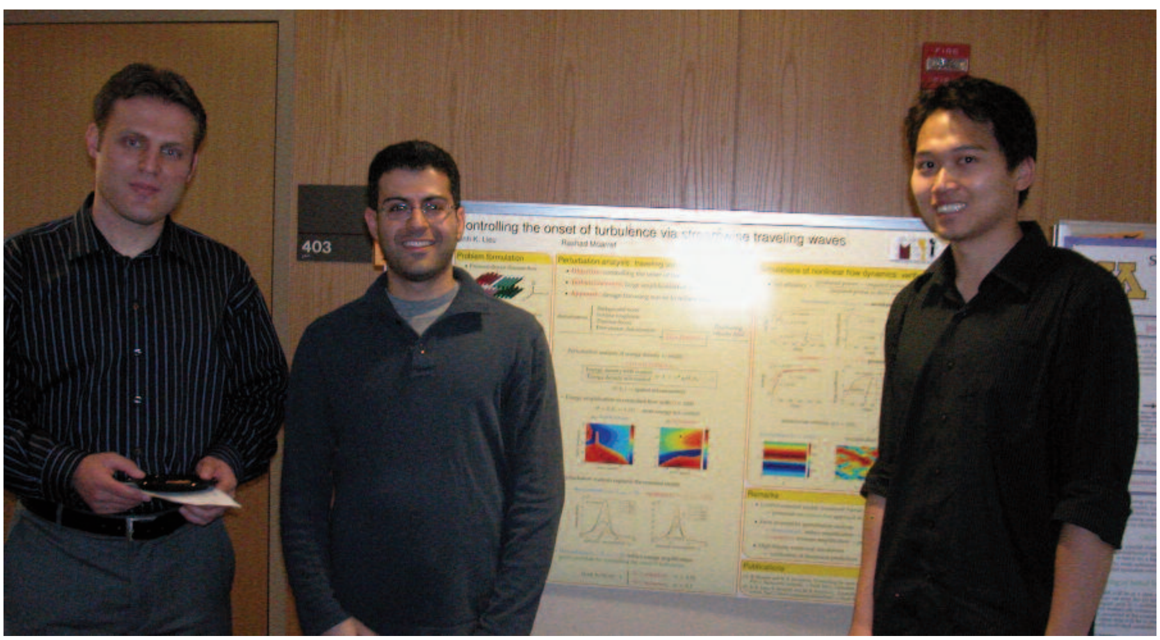

Figure 5. Prof. Mihailo Jovanovic and his graduate students Rashad Moarref and Binh Lieu (from left to right) at the MSI 25th Anniversary Research Exhibition. Their poster, which dealt with the research in this article, was selected as one of the five outstanding posters at the exhibition (see *www.msi.umn.edu/events/25th/index.html/*).