Flow Separation Control with Rotating Cylinders

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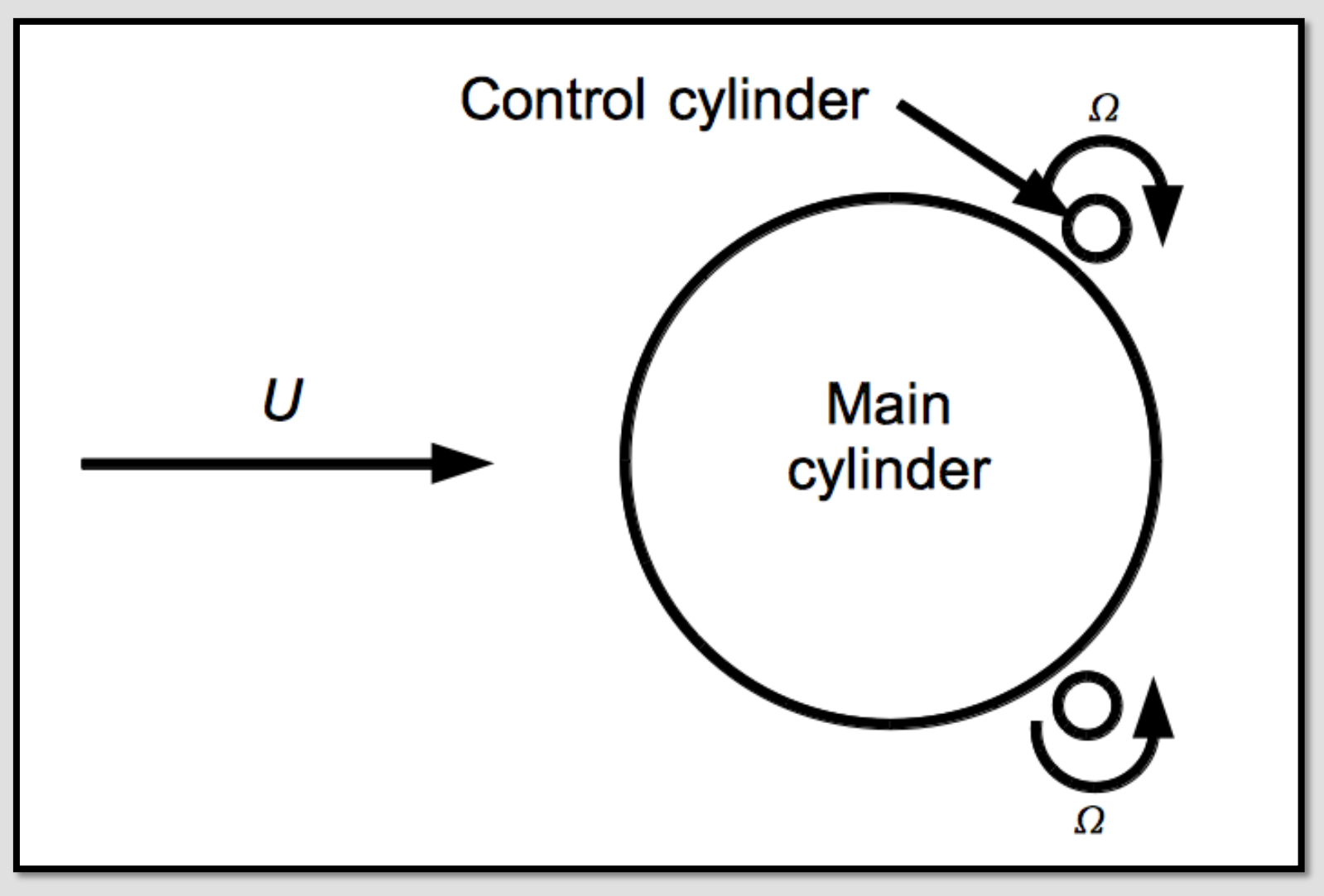
Goal: **Control flow separation to reduce hydrodynamic drag and oscillating lift forces on a bluff body in a cross flow.**

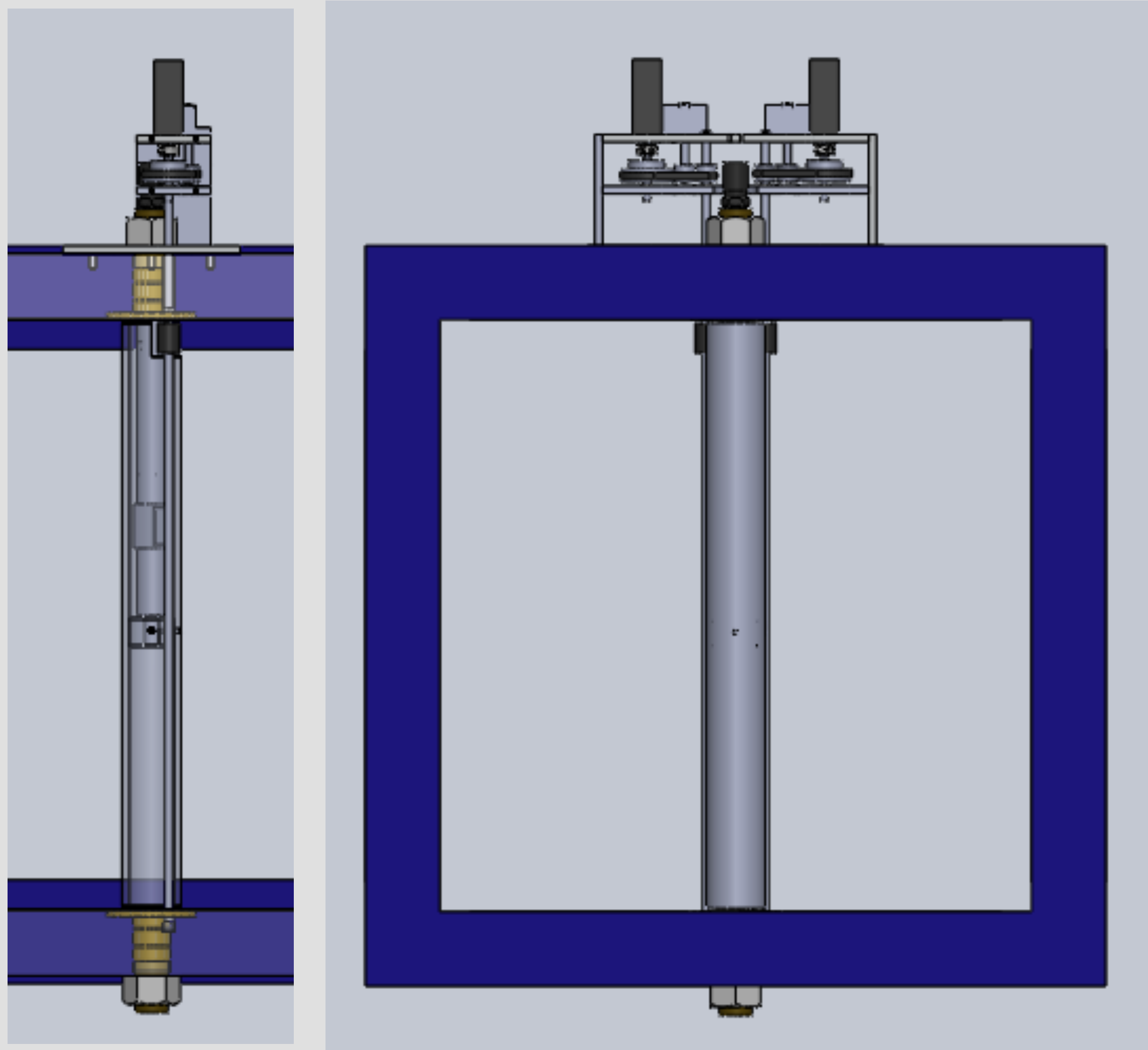
Introduction:

Flow separation dominates the hydrodynamic forces on bluff bodies, so efficient separation control has been and continues to be an area of intense investigative effort. Even streamlined bodies, such as ocean vehicles, experience flow separation when maneuvered sharply or subjected to unsteady flow fields. Active separation control strategies, which require power input, have been shown to effectively reduce drag. This poster discusses experiments in active flow separation control with rotating control cylinders at intermediate sub-critical Reynolds numbers. Rotating cylinders are positioned at 120 degrees to the incoming free stream in the immediate vicinity of a larger main cylinder. The control cylinders are rotated (see diagram at right) to inject momentum into the slow-moving boundary layer flow of the main cylinder. This delays flow separation and reduces drag. The control effort is expressed by the ratio of the surface speed of the control cylinders to the free stream velocity:

$$\xi = \frac{u_{surface}}{u_\infty}$$



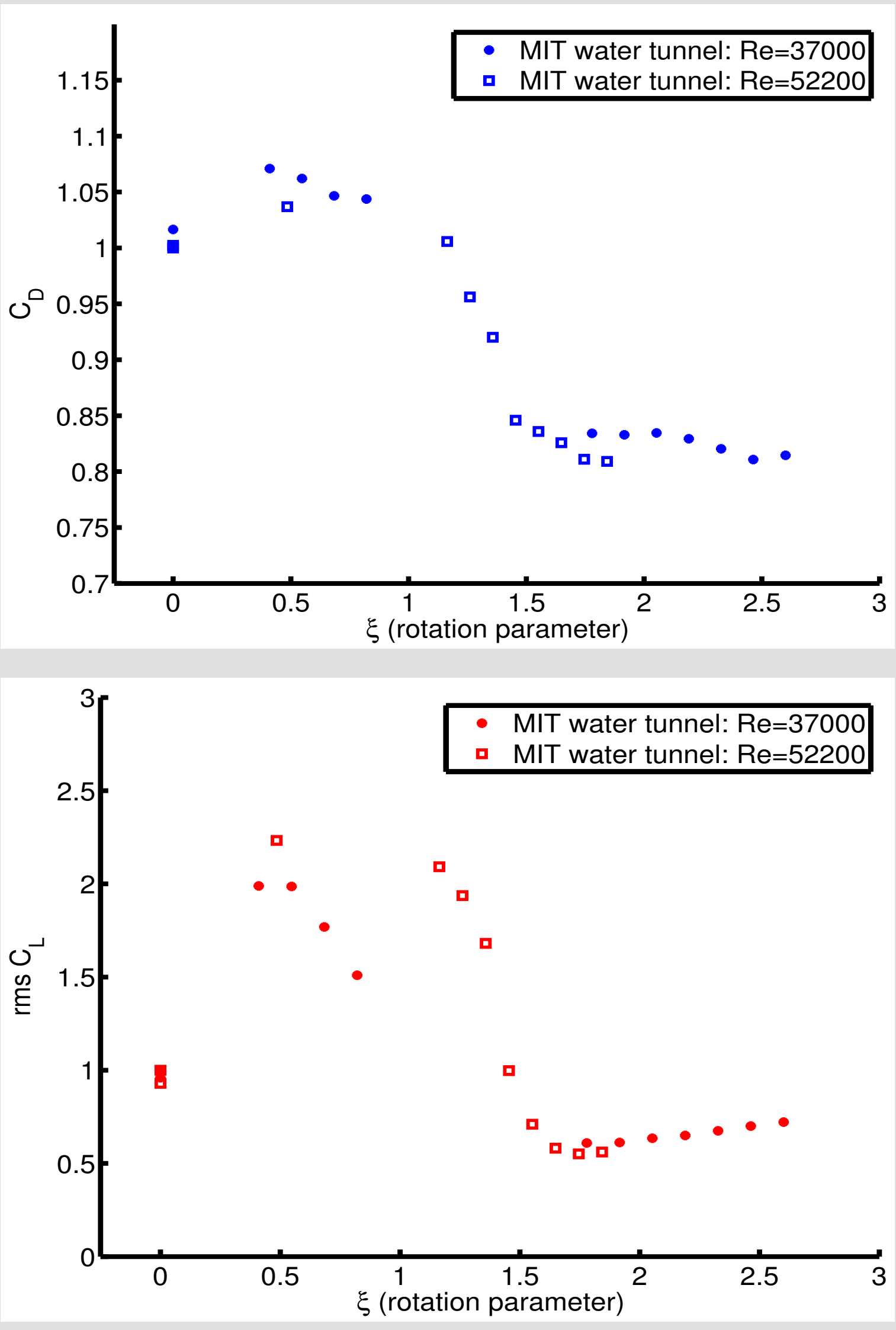
Water Tunnel Experimental Setup



An experimental apparatus was designed and fabricated to implement rotating cylinder control on the flow past a circular cylinder in the MIT water tunnel at Reynolds numbers in the intermediate sub-critical range (~50,000). The two images show a solid model of the apparatus. The right image shows the 10% blockage ratio of the model. The gap between each end and the wall is limited to 0.125 inches (1/16 of the cylinder diameter) to reduce three-dimensional end effects. The cylinder is mounted (left) at its center on an AMTI 6-axis force transducer on a sting that extends down from the top of the test section through the center of the cylinder. The control cylinders are powered independently with Yaskawa Sigma MM servo motors. A 1:3 gear ratio increases the rotation rate of the motor shaft to up to 10,000 rpm at the control cylinder, which moves the surface of the cylinders over three times as fast as the free stream velocity.

Drag and Lift Forces

The control effort is indicated by the rotation parameter, ξ, which is equal to the ratio between the surface speed of the control cylinders and the free stream velocity. As the rotation parameter increases to values greater than one, the drag force decreases by more than 15% and the root-mean-square value of the lift force fluctuation decreases by more than 45%.



Top: Drag force normalized by drag measured with zero control effort.
Bottom: RMS lift force fluctuations normalized by rms lift fluctuations with zero control effort.

Power Consumption

Active flow control strategies like this one require energy input, so it is important to consider system power. The power cost associated with moving a bluff body with flow control through a fluid is equal to the sum of power dissipated through drag and power supplied to the active flow control. Power dissipated by rotating cylinders can be estimated with a friction coefficient for flow over a flat plate with a flow velocity equal to the surface speed of the cylinder. An optimal operating point minimizes total power cost.

$$\mathrm{P}^*_{\mathrm{total}} = \frac{\mathrm{P}_{\mathrm{total}}(\xi)}{\mathrm{P}_{\mathrm{total}}|_{\xi=0}}$$

$$\mathrm{P}^*_{\mathrm{total}} = \frac{\mathrm{C_D}(\xi)}{\mathrm{C_D}|_{\xi=0}} + 2\pi \frac{\mathrm{C_f}(\mathrm{Re_{rot}})}{\mathrm{C_D}|_{\xi=0}} \frac{\mathrm{d}}{\mathrm{D}} \xi^3$$

The power dissipated by flow control is dominated by the ratio of the flat plate friction coefficient to the drag coefficient of the bluff cylinder. At Reynolds numbers greater than 10,000, which is the range of Reynolds numbers for flow past ocean vehicles, this ratio drops to less than 1%. Simulations of a similar flow control mechanism by Mittal (2001) at Reynolds number 10,000 calculated power dissipation by rotating cylinders at ξ=5 to be 0.6% of power dissipation due to drag. The hydrodynamic cost is thus trivial over the expected operating range for rotating control cylinders. This analysis does not include power dissipation that occurs between the motors driving the control cylinders and the cylinders themselves.

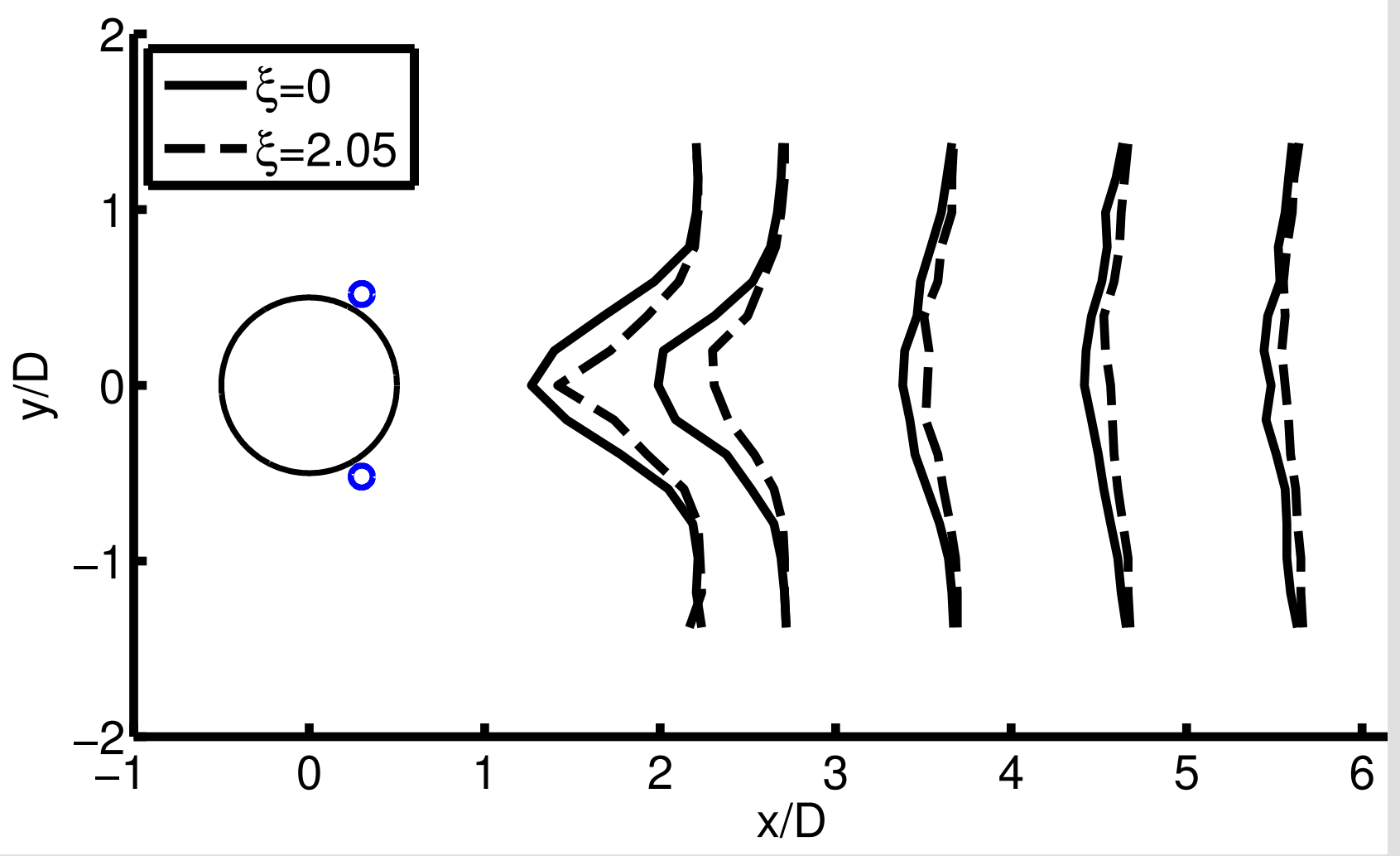
Mean Wake Flow Field

Laser Doppler Velocimetry

Laser doppler velocimetry (LDV) is a non-intrusive velocity measurement technique. The flow is seeded with small (20 micron diameter in this experiment) neutrally buoyant particles, which trace the flow. Two lasers are shone into the flow such that they intersect. Interference in the volume in which the lasers intersect results in a “fringe pattern” of parallel bands of high and low intensity light. The velocity of a particle that passes through the intersection volume is calculated by measuring the intensity of reflected light, which is modulated by the fringe pattern at a frequency determined by the particle’s velocity.

Mean Velocity Profiles

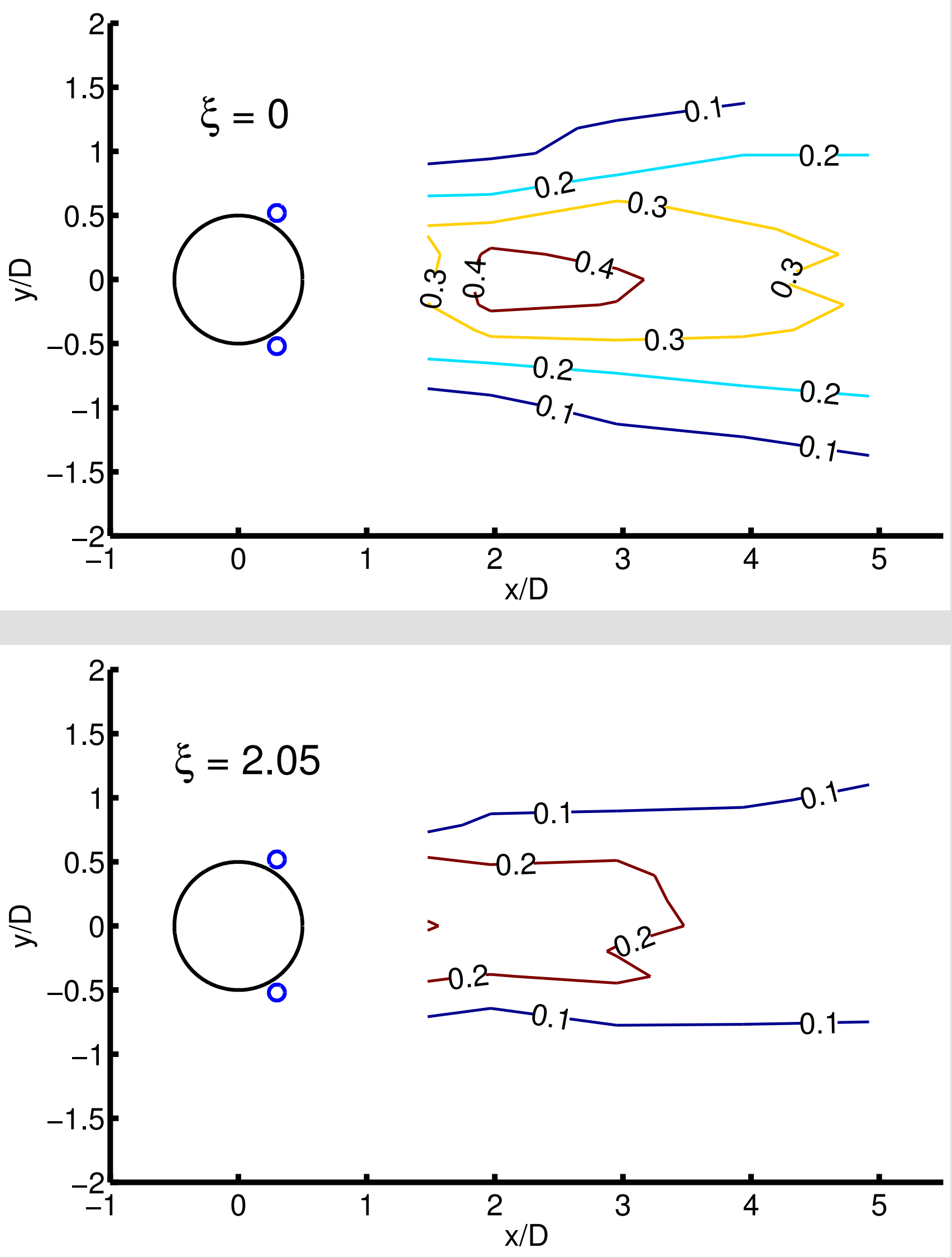
In addition to directly measuring forces on the cylinder with strain gauges, the mean forces can be calculated from the mean flow field using momentum conservation: the change in momentum of the fluid as it moves past the cylinder is equal to the force that the cylinder exerts on the fluid. Mean stream-wise wake velocity profiles are plotted below. It is clear that rotating the control cylinders at ξ=2 reduces the wake momentum deficit, which is consistent with the measured drag reduction.



Above: The stream-wise velocity deficit is plotted in the wake of a cylinder both with and without rotating control cylinders. Rotating the cylinders narrows the wake and reduces the wake velocity deficit.

Velocity Fluctuations

The wake velocity fluctuations provide insight into vortex shedding. Contours of RMS transverse velocity fluctuations are plotted below. Vortex shedding causes strong oscillating lift forces, which can result in dangerous vibrations and greater drag force. Without flow control, strong vortices in the wake create a large region of unsteady flow. Rotating the control cylinders at ξ=2 reduces the strength of vortices shed into the wake, which is consistent with the measured reduction in RMS lift force.



Contours of the root-mean-square transverse velocity component, normalized by the free stream velocity, are plotted on top of the mean velocity field variation from the free stream (black arrows). The free stream is directed from left to right. **Top:** The control cylinders (blue) are not rotating. **Bottom:** The control cylinders rotate such that the cylinder surface moves at a speed twice that of the free stream flow.

Future work

Future work will include investigating closed-loop control of bluff body flow separation with feedback from a force sensor and an array of pressure sensors. Additionally, a separation control mechanism based on this two-dimensional work will be designed for control of three-dimensional vortex separation on sharply maneuvering vehicles.

Acknowledgements

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