Linear control of 3D disturbances on a flat-plate

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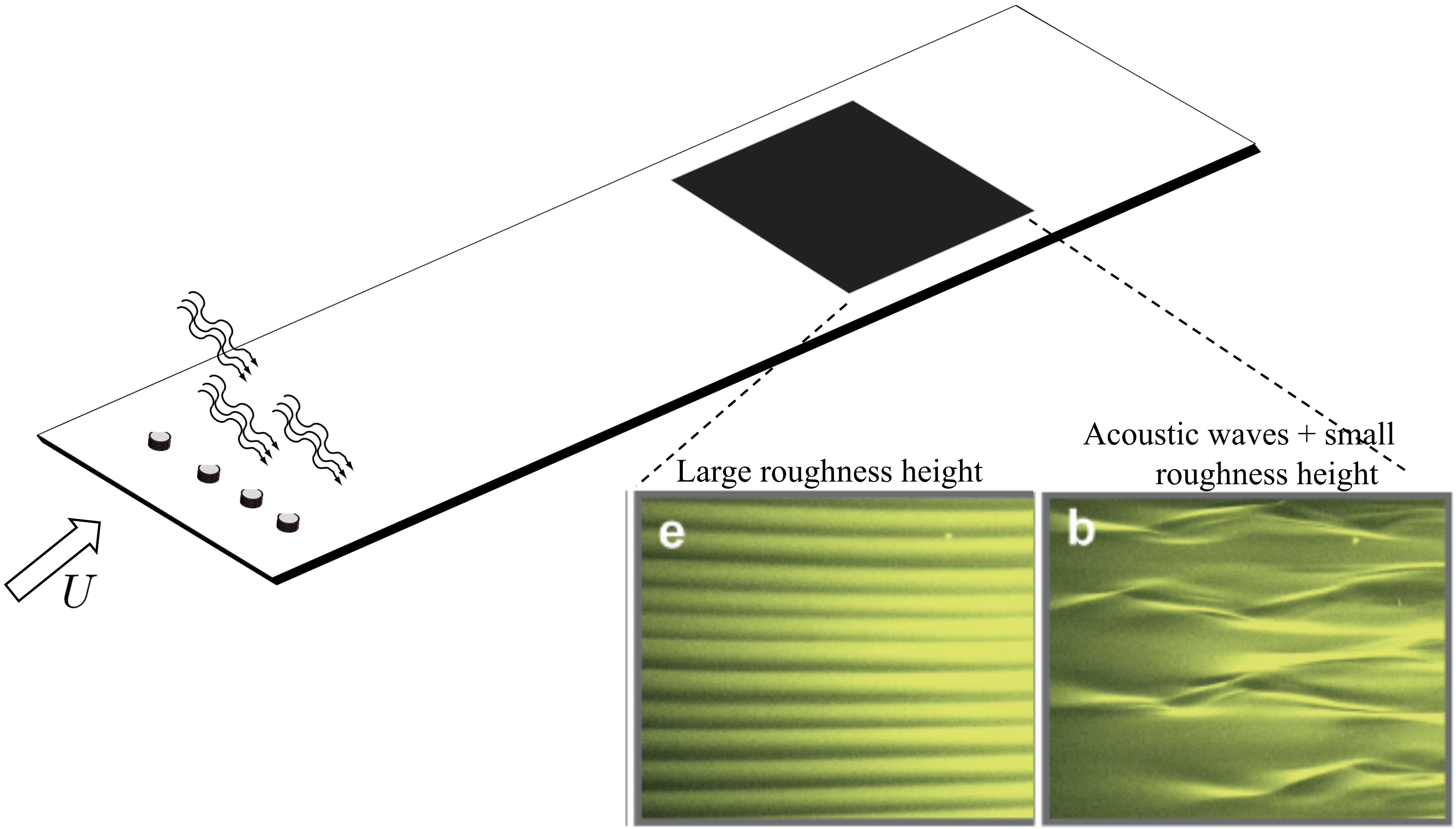
7th IUTAM Symposium on Laminar-Turbulence Transition
June 23-26, 2009, Stockholm, Sweden

Transition control

- Sensitive dynamics → response depends on initial conditions



- Reduce sensitivity to external disturbances → transition delay

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Transition control

- No exact knowledge of disturbances → Feedback control
  - Inputs: disturbances & actuators
  - Outputs: sensors for estimation & performance

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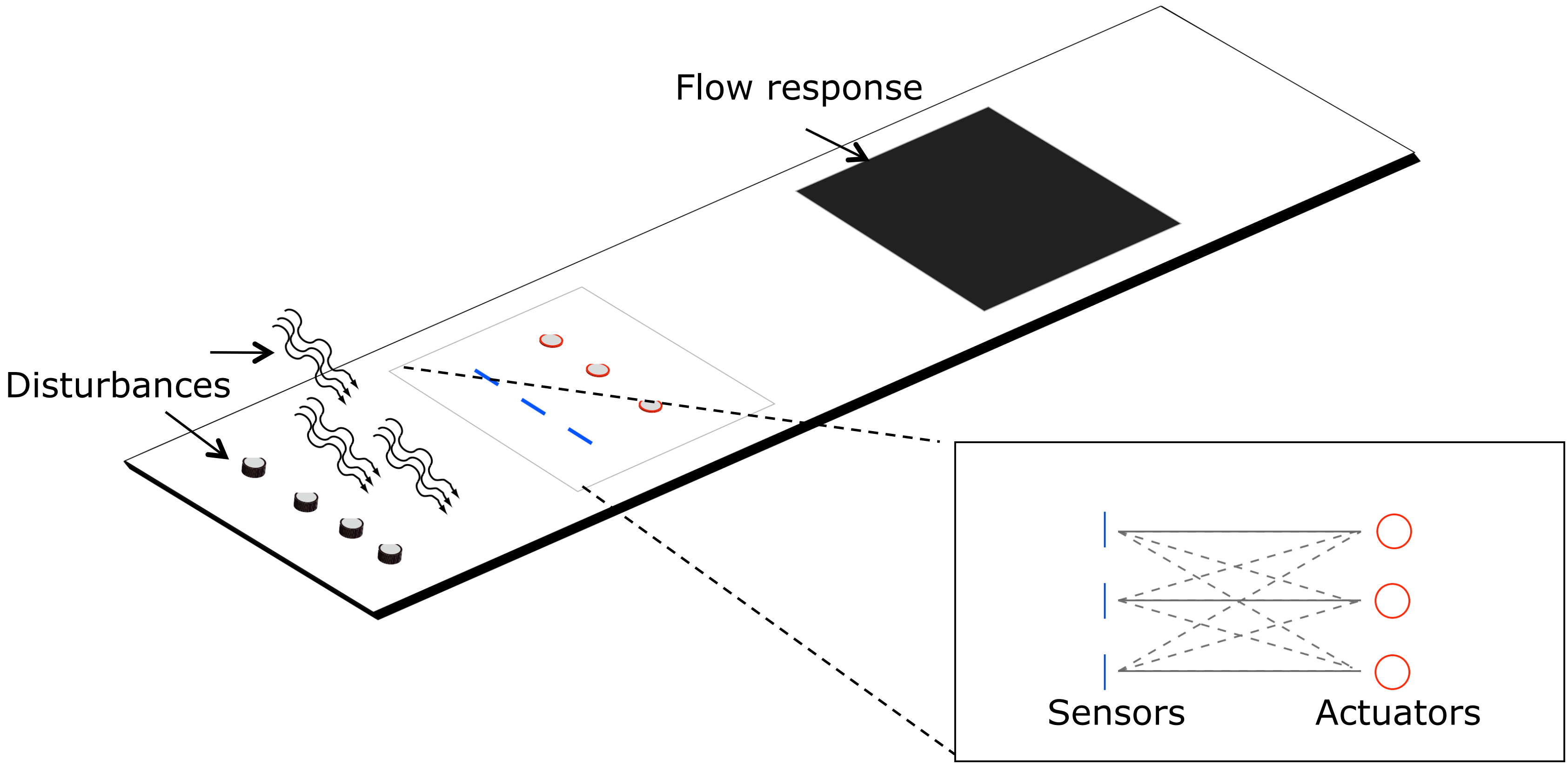
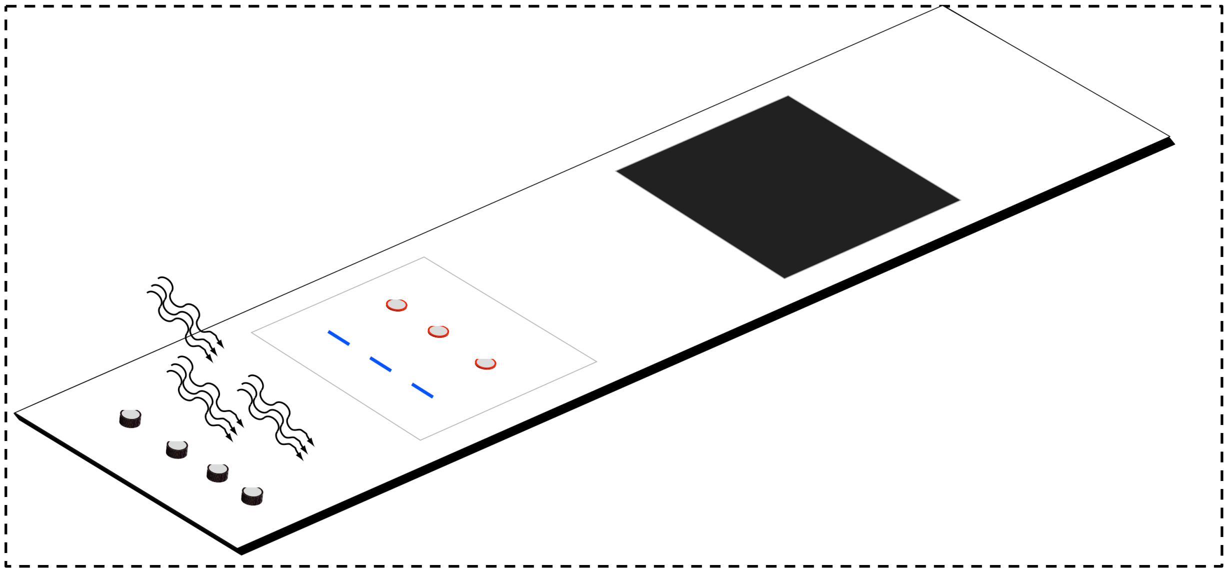


$Re = U\delta_0^*/\nu = 1000$

$500 \times 20 \times 80$ (Box)

$384 \times 81 \times 80$ (Grid)

Control Design – 4 Steps



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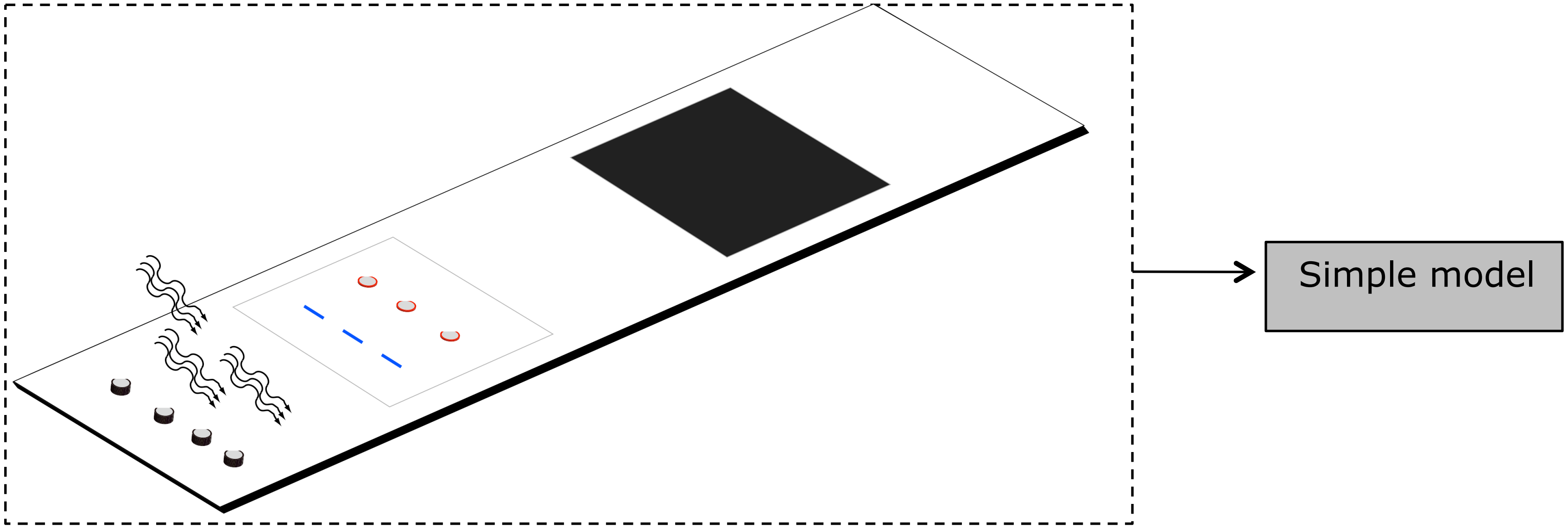
1. Construct plant: Flow, inputs, outputs

Control Design – 4 Steps



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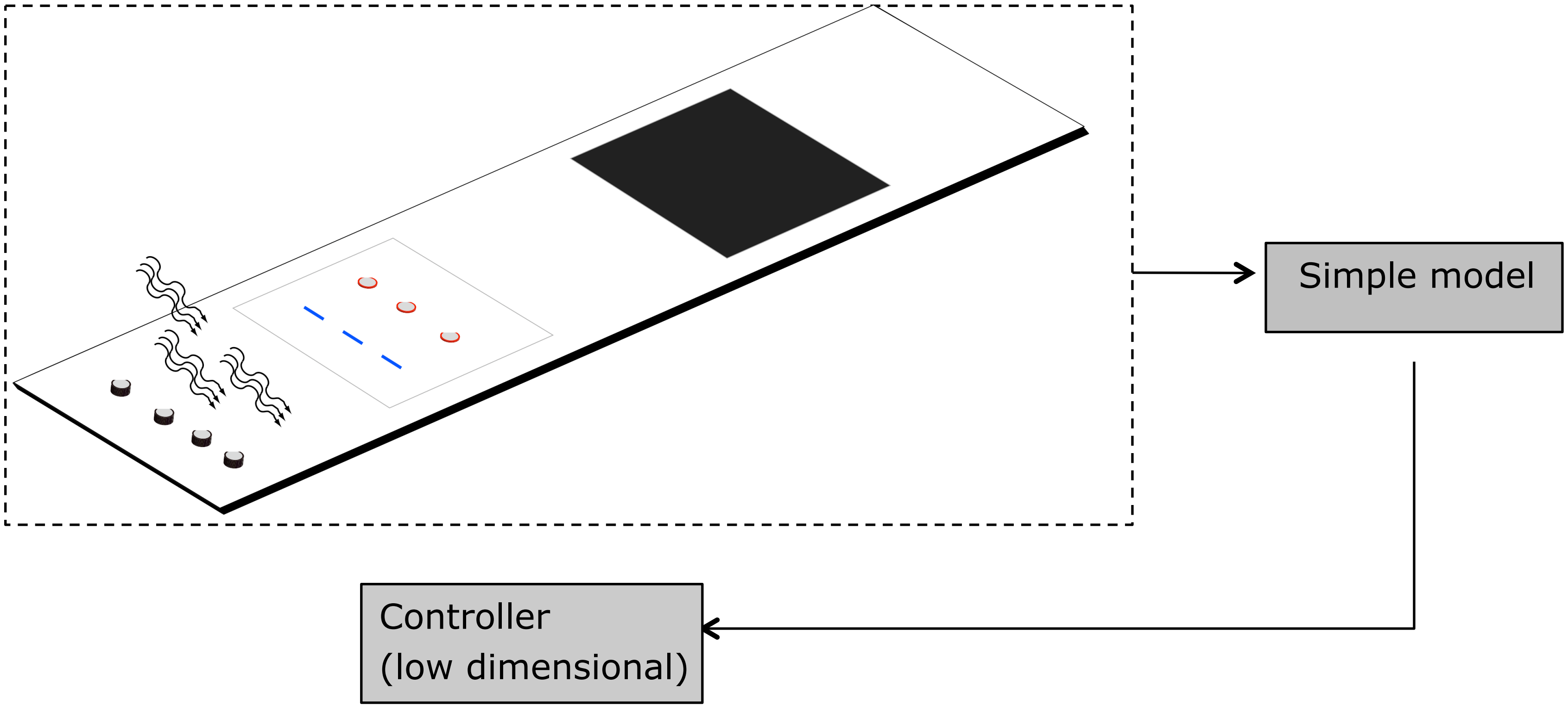
1. Construct plant: Flow, inputs, outputs
2. Construct reduced model from the plant using balanced truncation

Control Design – 4 Steps



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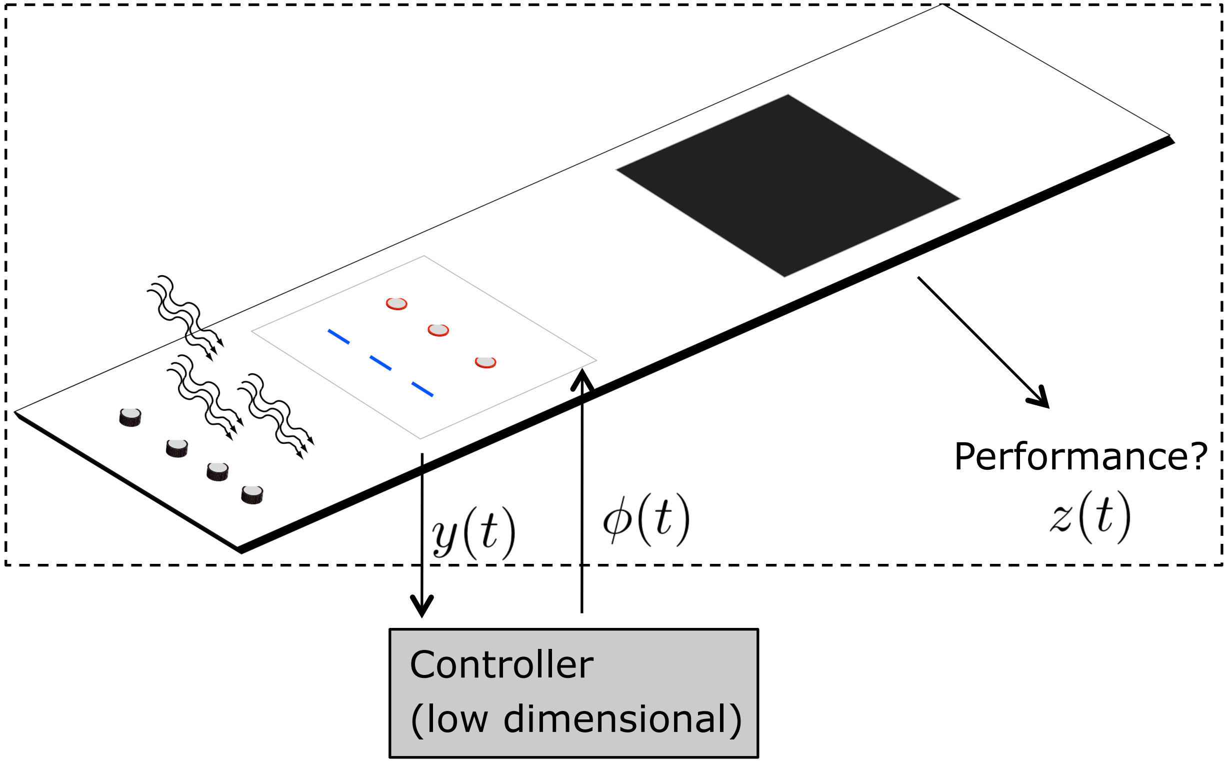
1. Construct plant: Flow, inputs, outputs
2. Construct reduced model from the plant using balanced truncation
3. Design controller using the reduced-model

Control Design – 4 Steps



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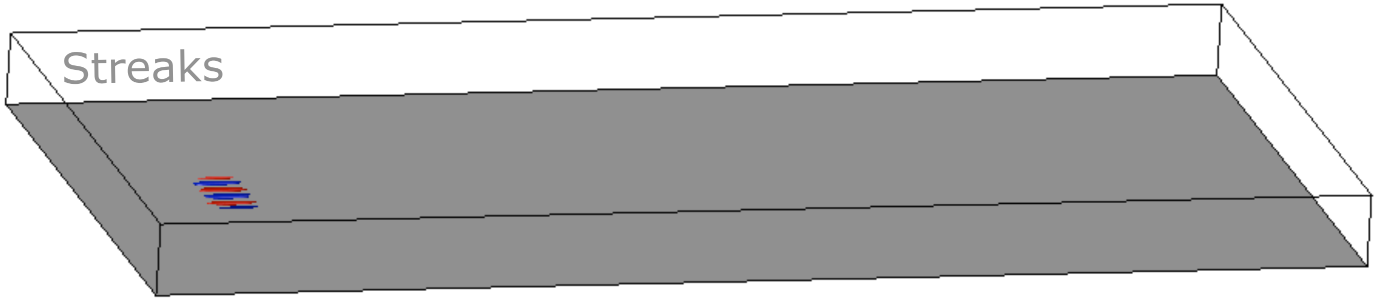
1. Construct plant: Flow, inputs, outputs
2. Construct reduced model from the plant using balanced truncation
3. Design controller using the reduced-model
4. Closed-loop: Connect sensor to actuator using the reduced controller

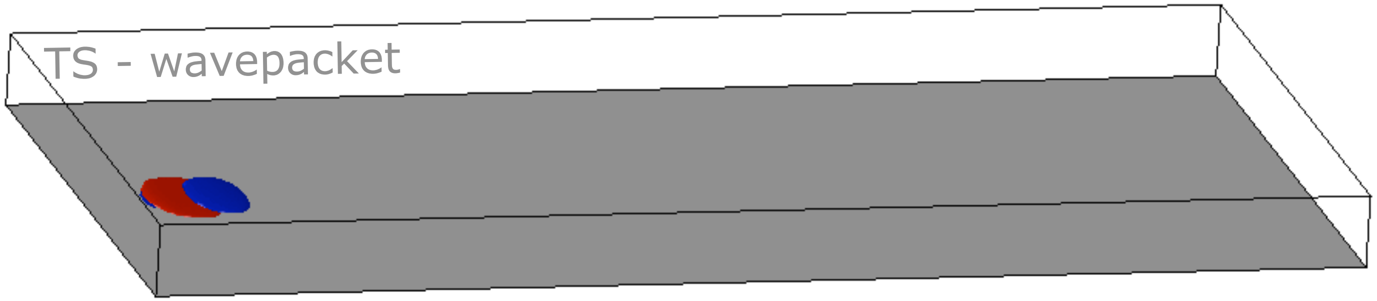
Run small controller online and evaluate closed-loop perfomance

Inputs & Outputs

- Inputs: Optimal disturbances giving largest growth at time T (Ref: Monokrousos et. Al. (IUTAM 09, P30))
  - Short time: Lift-up mechanism → streaky structures



  - Long time: Orr mechanism/TS wavepacket → 2D wavepacket



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Positive u-vel
Negative u-vel

- Outputs: leading POD modes → most of energetic structures

Projection onto balanced modes

- Reduced-order model via a Galerkin (oblique) projection onto spatial modes
  - POD modes – captures most energetic structures
  - Global eigenmodes – captures instability dynamics
  - Balanced modes – captures the input-output behavior

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- Snapshot method to compute balanced modes (Rowley, 2005)
  1. Collect flow field snapshots from impulse response simulation for each input
  2. Collect flow field snapshots from impulse response simulation of the adjoint equation for each output
  3. One small SVD (size: adjoint snapshots x forward snapshots)

Balanced mode #1: TS wave

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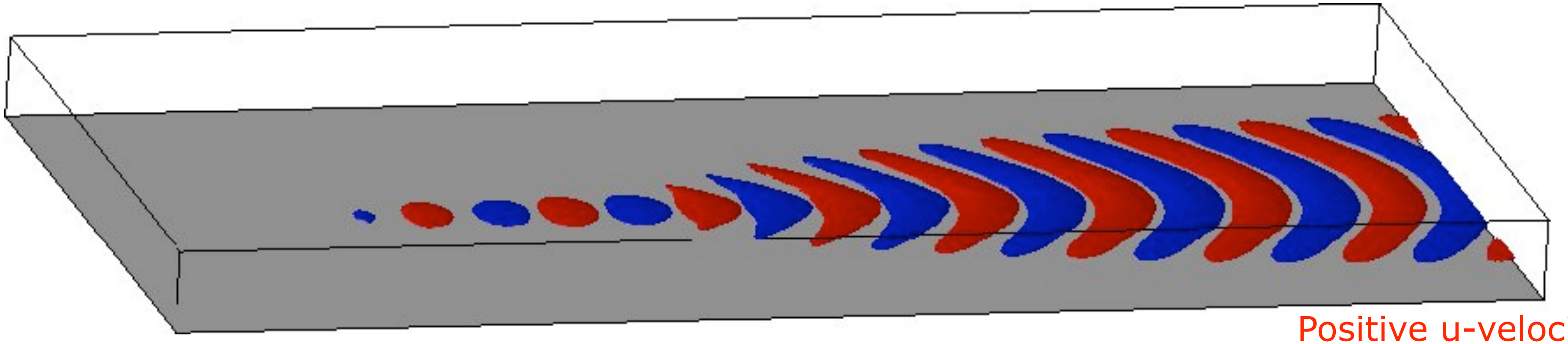
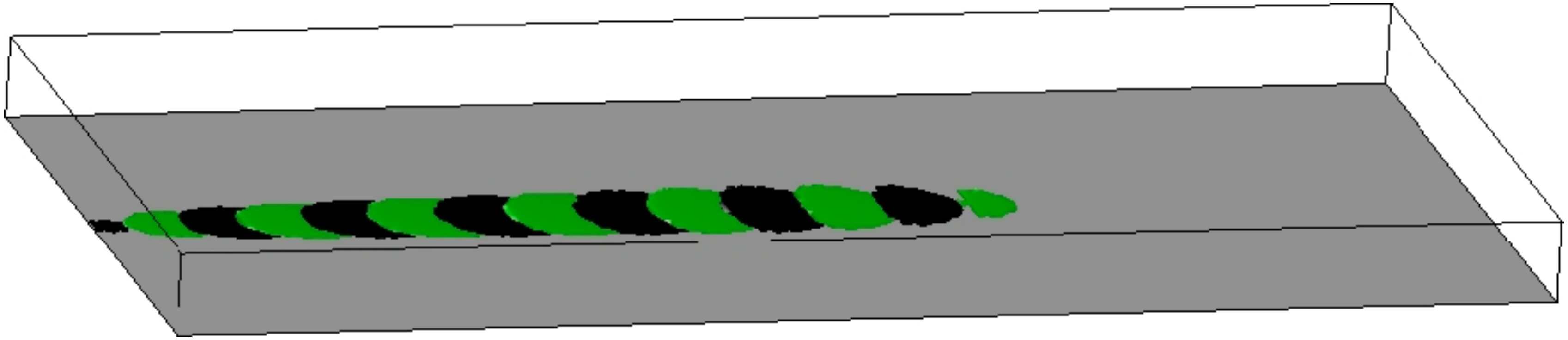
- Direct mode – wavepacket downstream



Positive u-velocity
Negative u-velocity

- Adjoint mode – upstream tilted structures upstream



Positive u-velocity
Negative u-velocity

- Streamwise non-normality

Balanced mode #11: Streak

Positive u-velocity

Negative u-velocity

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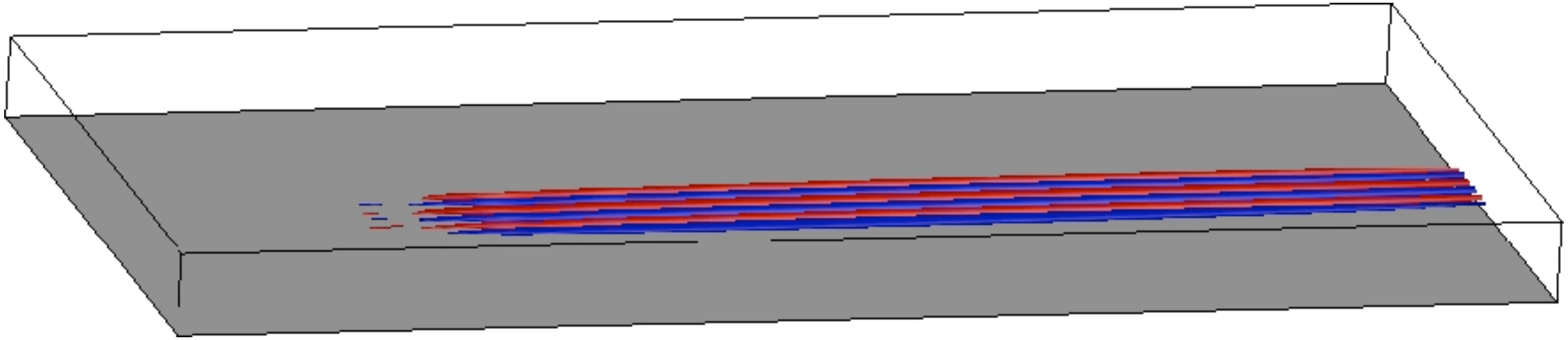
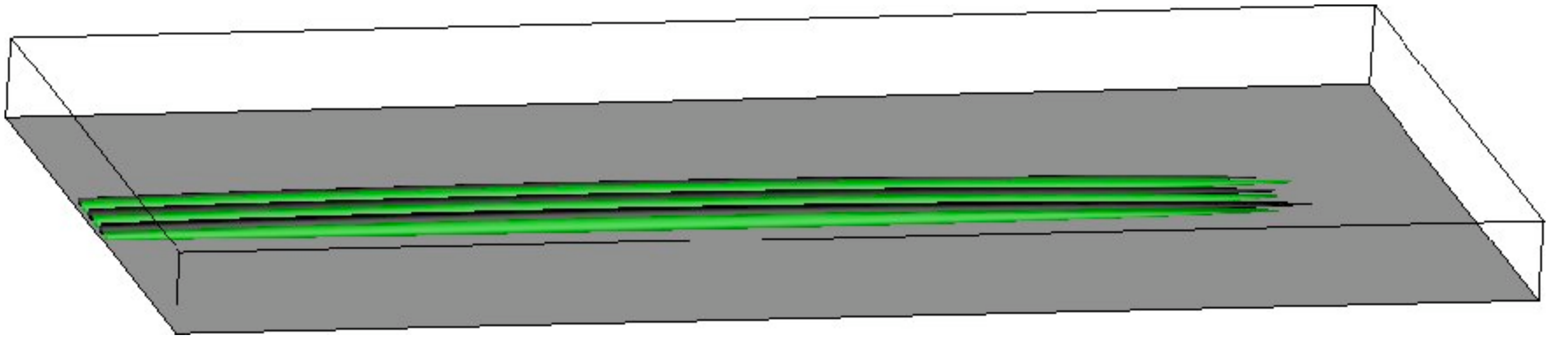
- Direct mode – streaky structures in u



- Adjoint mode – streamwise vortices (v,w)



Positive v-velocity

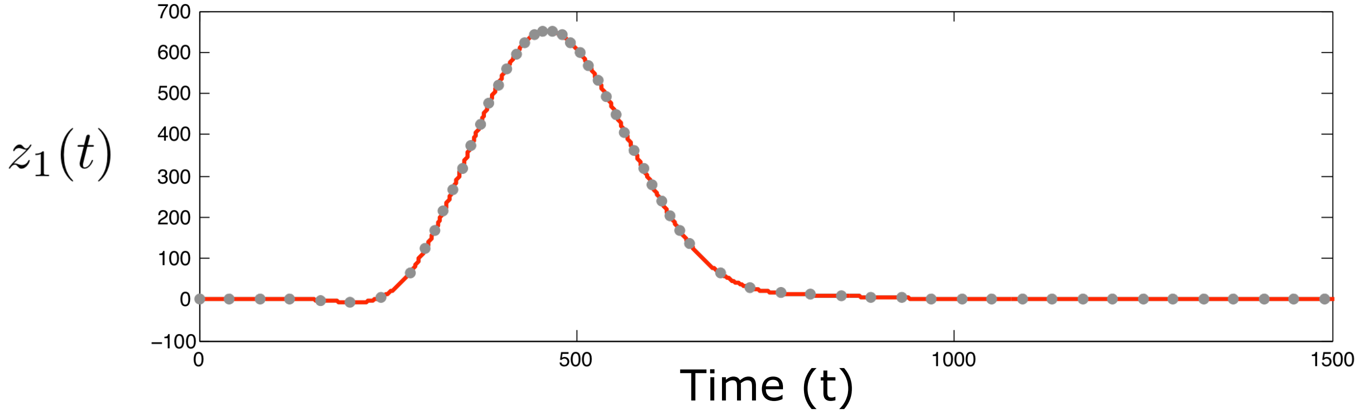
Negative v-velocity

- Component-wise non-normality

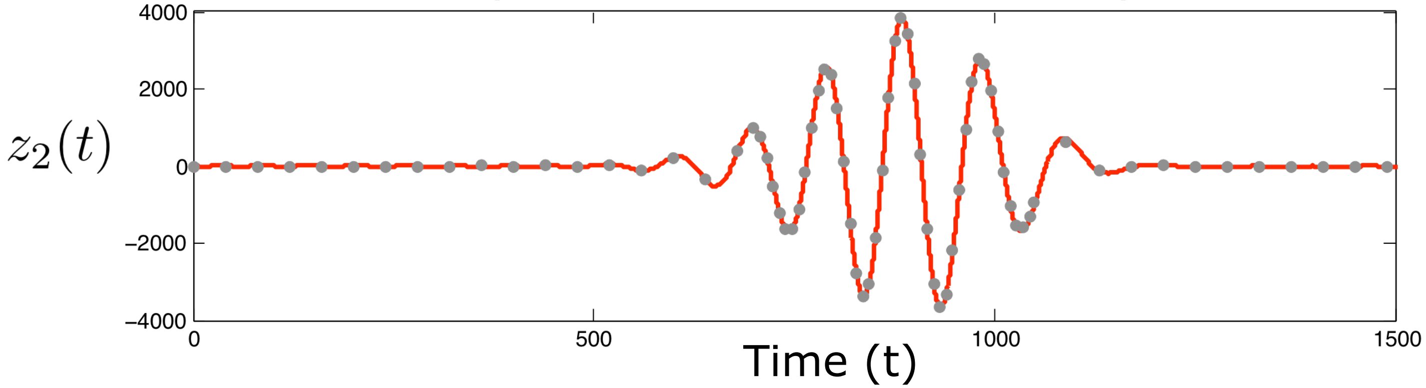
Reduced-order model (size=50)

- Compare output signals of DNS and small model for impulsive input

- Initial condition: Streamwise vortices



- Initial condition: Upstream tilted 2D wavepacket



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DNS: n=7 000 000

ROM: m=50

Reduced-order controller

- B2/C2: actuators/sensors:
  - Localized wavepackets near the wall
- C1: objective functions
  - A number of localized spanwise Fourier function → defines a spatial region downstream
- Design H2/LQG controller
  - Small: 50 degrees of freedom
  - Optimal: one Riccati for estimation & one Riccati for control
  - Control penalty: l=1, degree of measurements noise: $\alpha = 0.1$

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Control performance

- Response to stochastic (white noise) excitation
- RMS of streamwise velocity component

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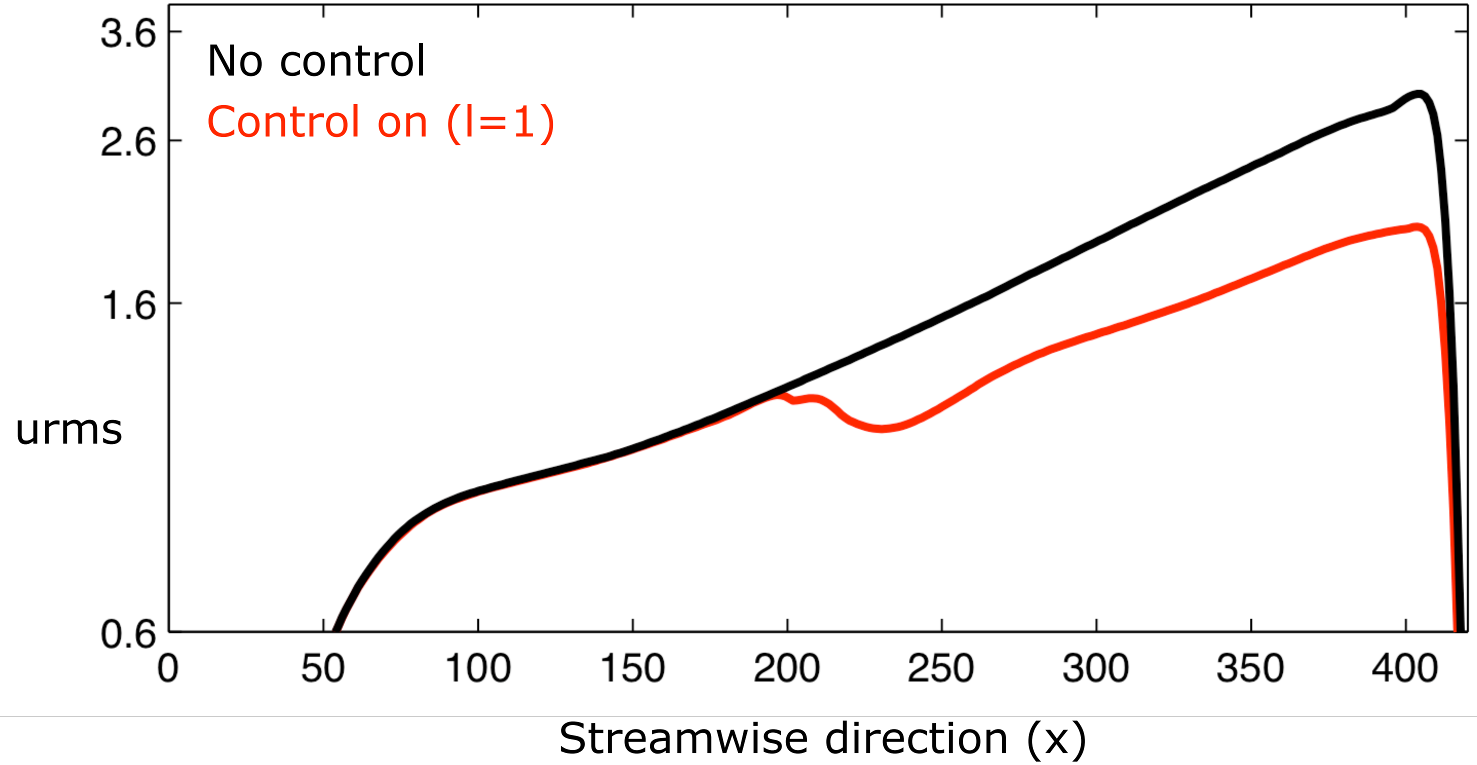

Outlook

- Design a controller that effeciently reduced disturbance growth for any disturbance
  - Design “realistic” actuators and sensors
  - Extend basis used for the objective function to span larger domain

- Compensate the nonlinear flow

- Move to wind-tunnel:
  - Use the computed low-dimensional controller
  - Use the numerical model for parametric studies (i.e. actuator/sensor shapes and locations, control configuration etc…)

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