Friction drag reduction via closed-loop control with plasma actuators

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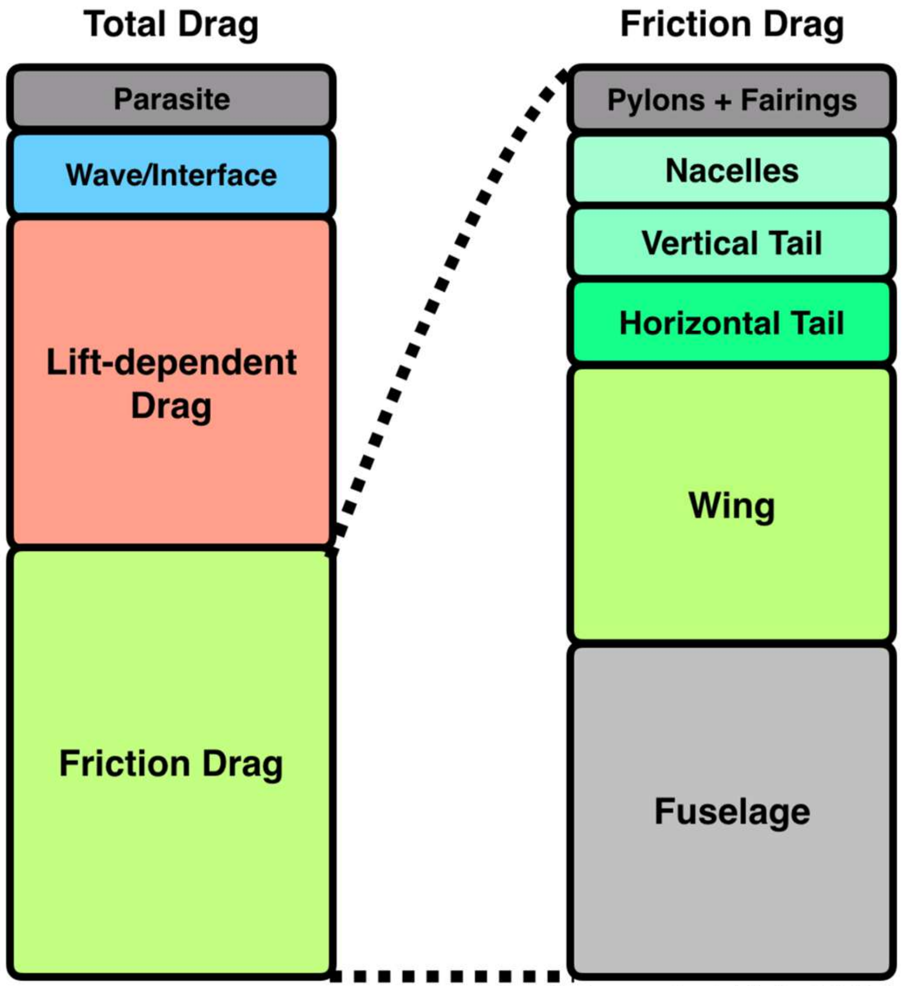
Drag sources



G. Schrauf, AIAA 2008

- Possible areas for laminar flow control: laminar wings, tail, nacelles

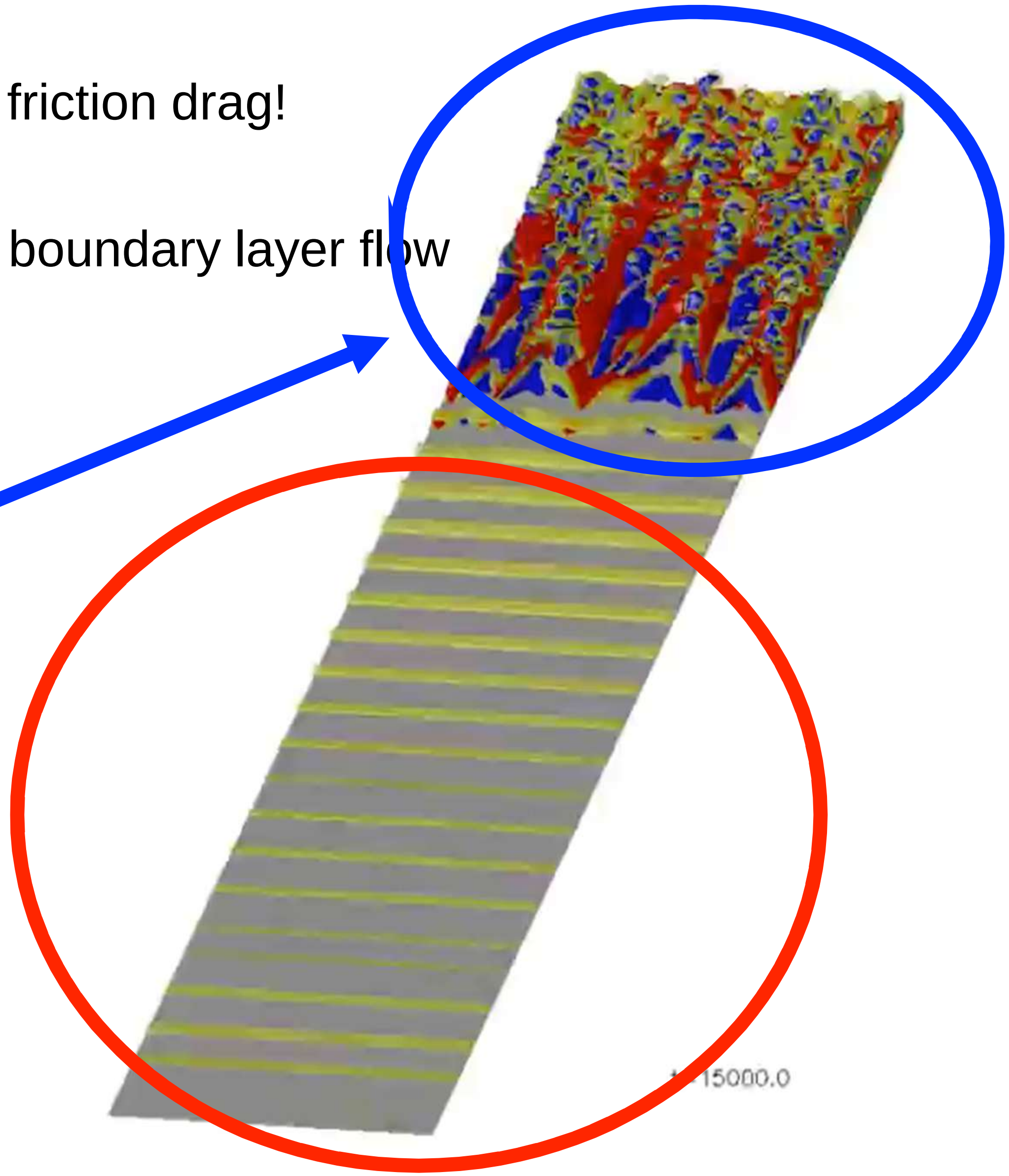
15% lower fuel consumption!

Friction drag

- Turbulent regime ➔ high friction drag!
- Disturbances (TS-waves) in the boundary layer flow lead to the turbulent regime

Turbulent regime

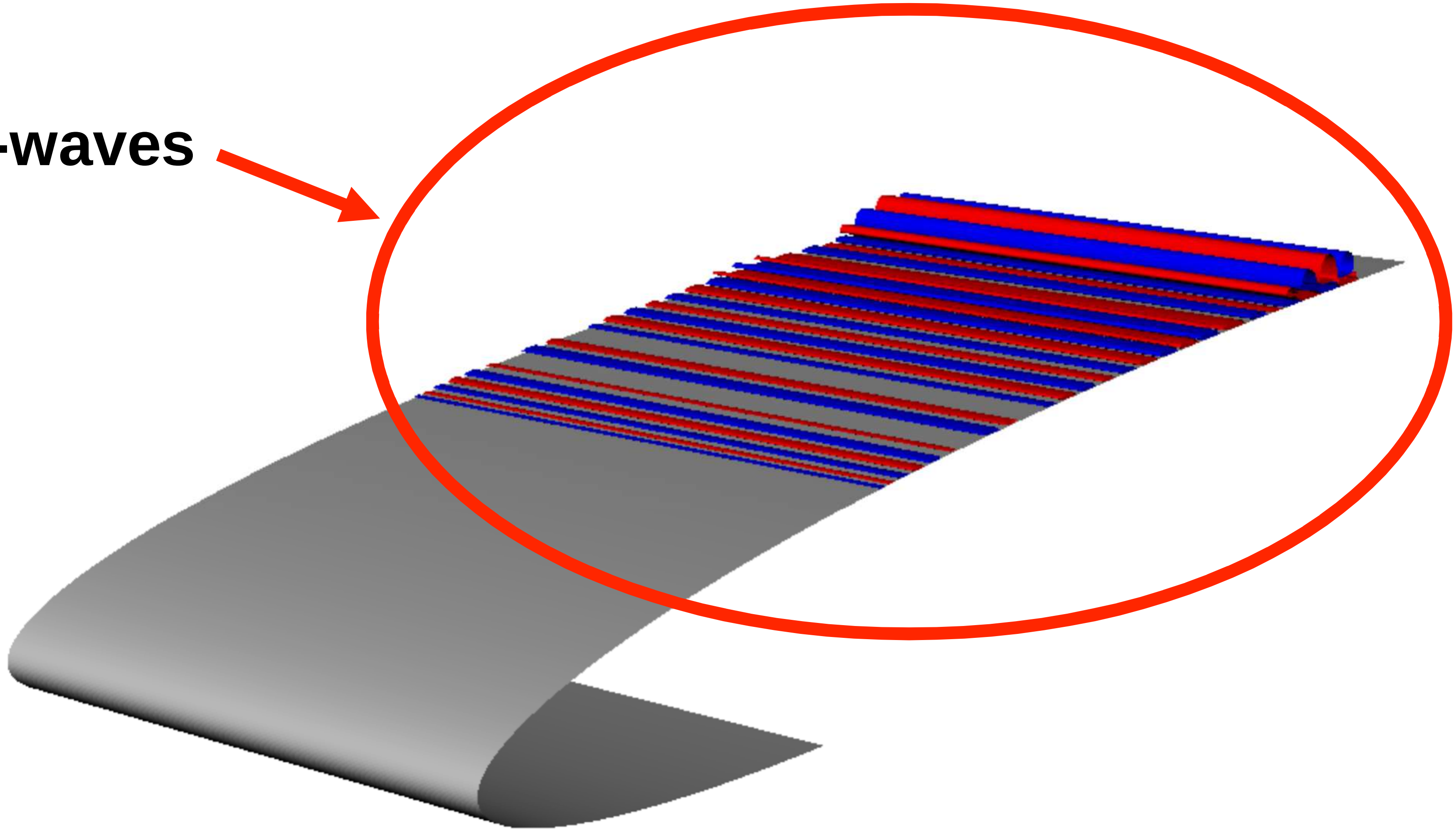
TS-waves



Direct Numerical Simulation

Friction drag

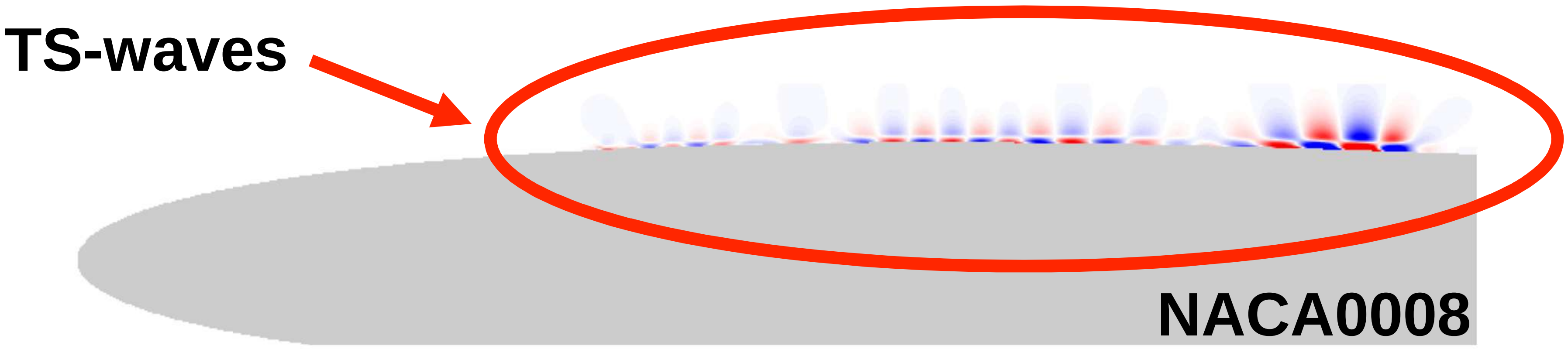
TS-waves



NACA0008

Direct Numerical Simulation

Method

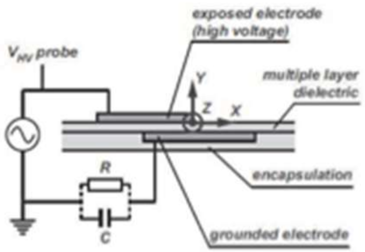


Direct Numerical Simulation

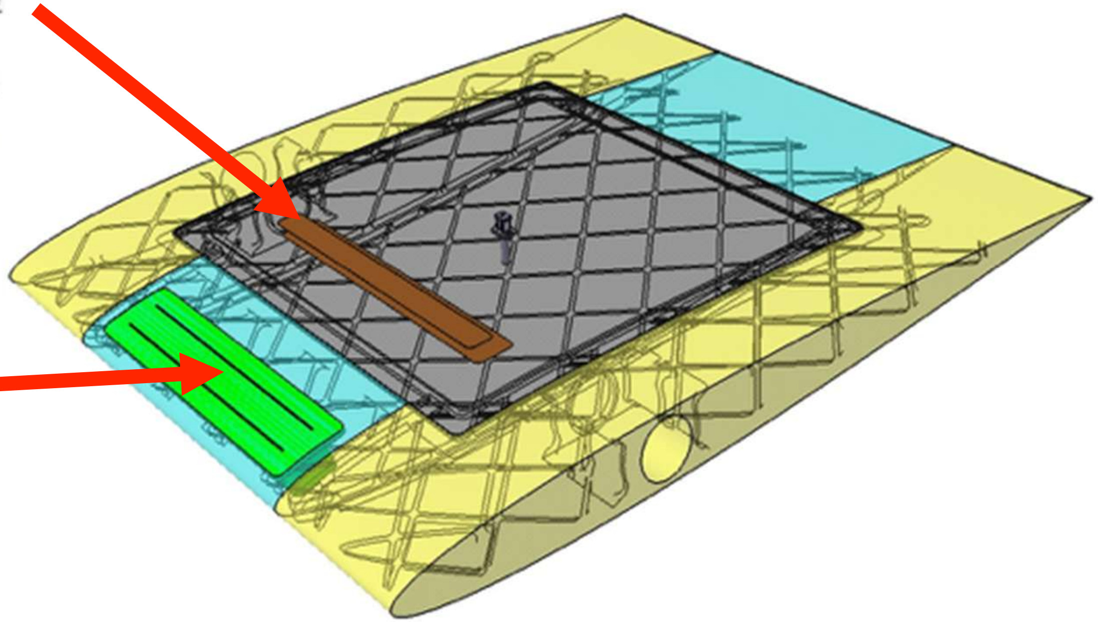
- Flow control to delay laminar-to-turbulence transition by damping TS-waves
- Active method: energy given to the flow (plasma actuator)
- Control theory to modulate the actuation signal

Experimental setup

Plasma actuator

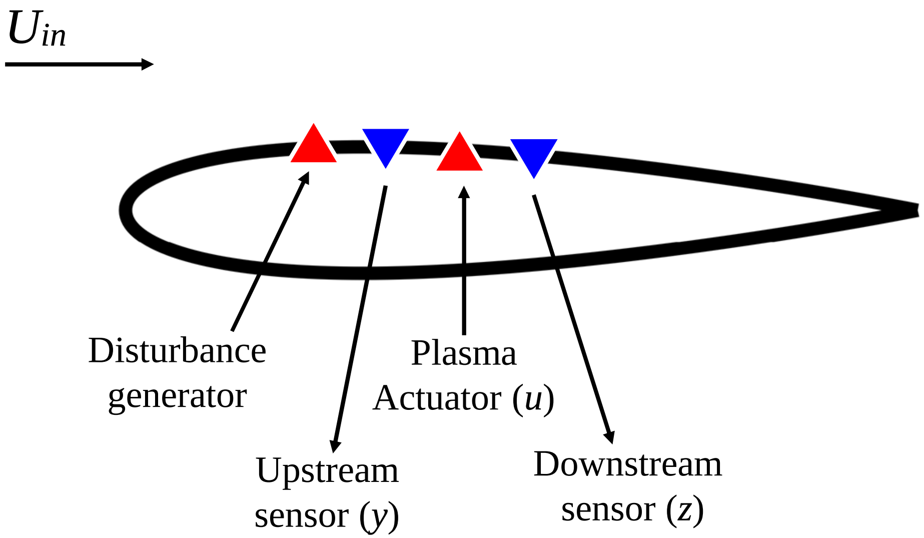


Disturbance generator



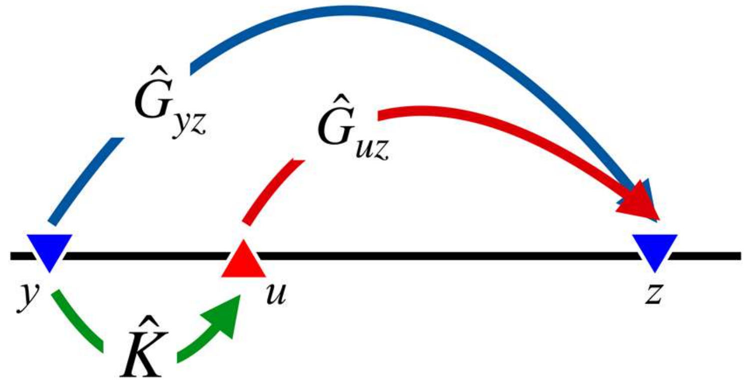
CAD model for wind-tunnel experiments (SAAB)

Control methodology



$$\hat{u}(\omega) = \hat{K}(\omega)\hat{y}(\omega)$$

$$\hat{K}(\omega) = \frac{\hat{G}^*_{uz}(\omega)\hat{G}_{yz}(\omega)}{\hat{R} + \hat{G}^*_{uz}(\omega)\hat{G}_{uz}(\omega)}$$



- Actuation signal based on upstream sensor

$$u(t) := \int_0^t K(\tau)\, y(t-\tau)\,\mathrm{d}\tau$$

- $\hat{K}$ computed via the IFFC control law (DNS & experiments), LQG and FxLMS (DNS)

Plasma actuator

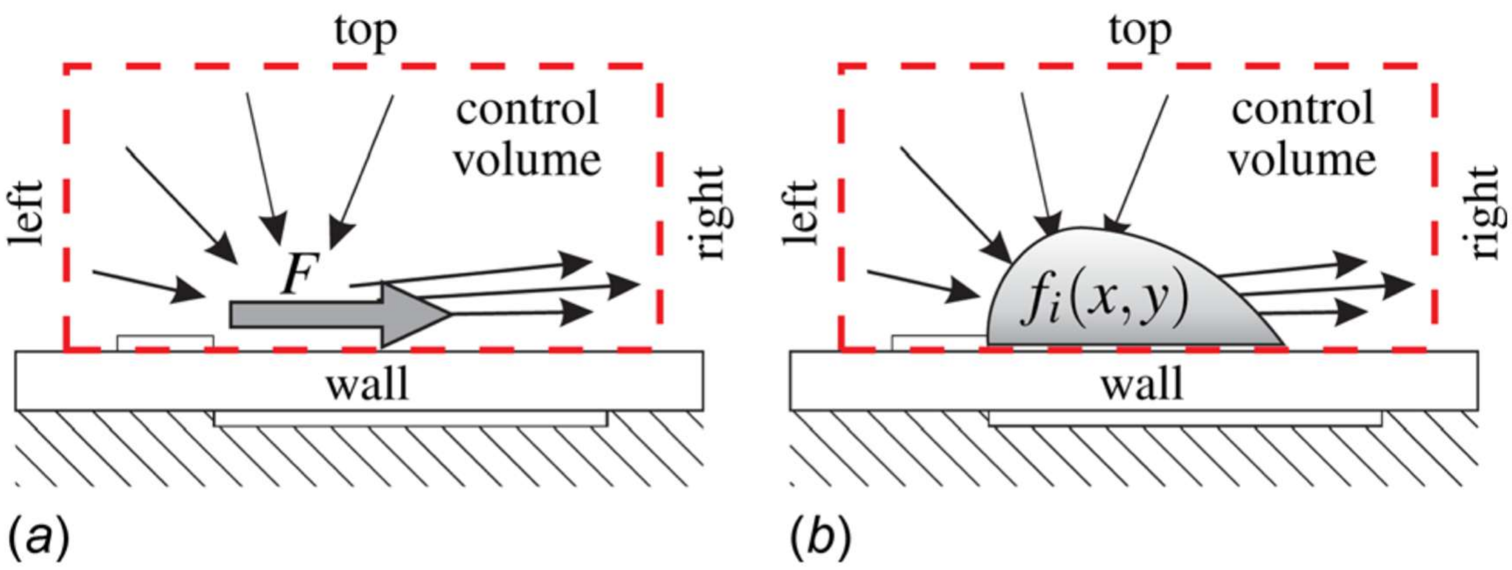


Fig. 23 Typically applied CV with boundary nomenclature as used in the present work: (*a*) integral force value *F*, and (*b*) force distribution *f*(*x*, *y*). Velocity distribution is sketched with black arrows, and force (distribution) is shaded gray. (Reprinted with permission from Kriegseis et al. [149]. Copyright 2012 by Jochen Kriegseis.)

Plasma actuator

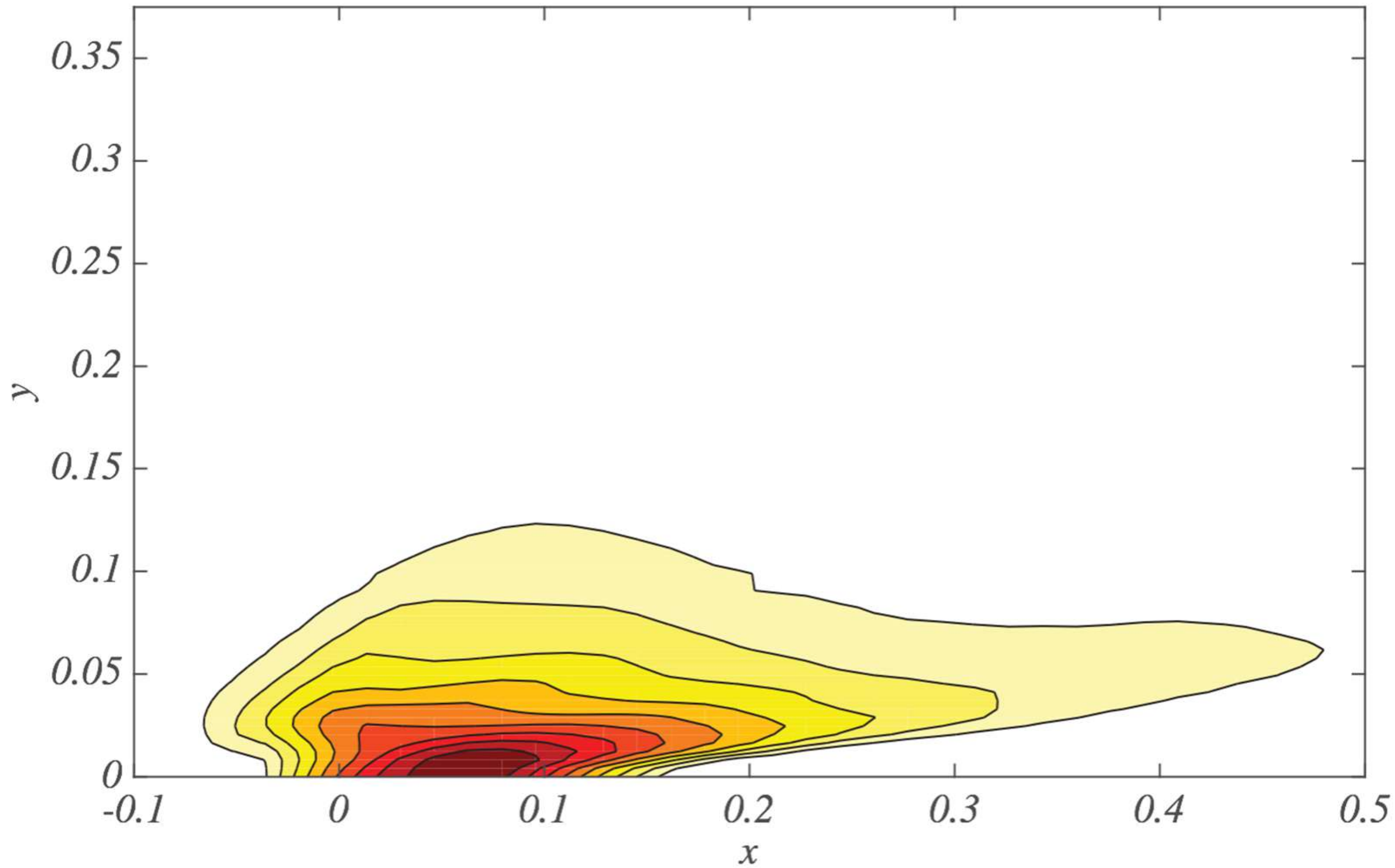
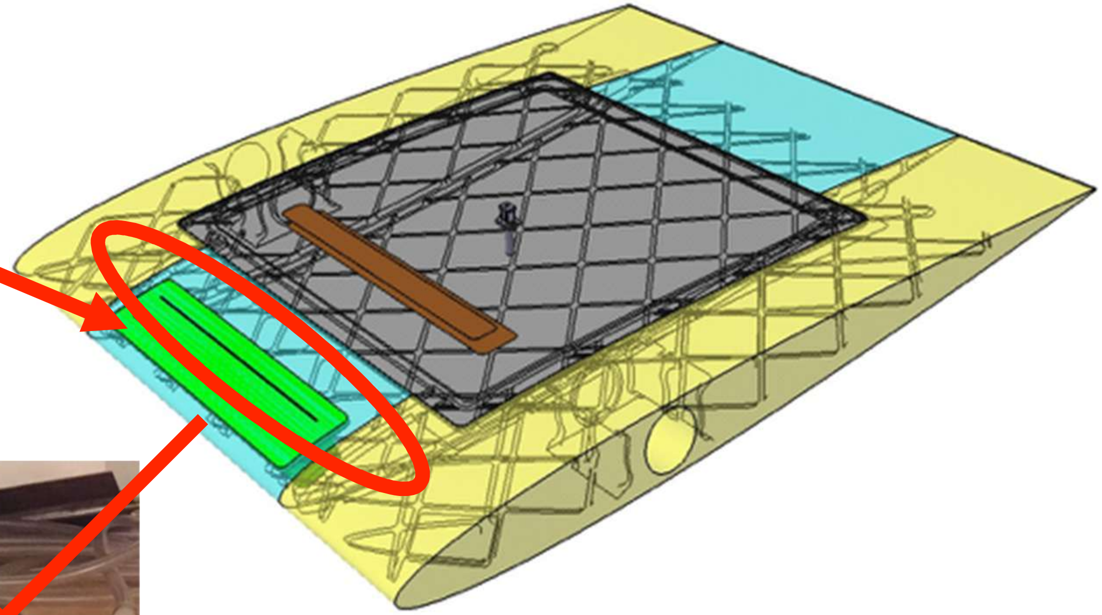
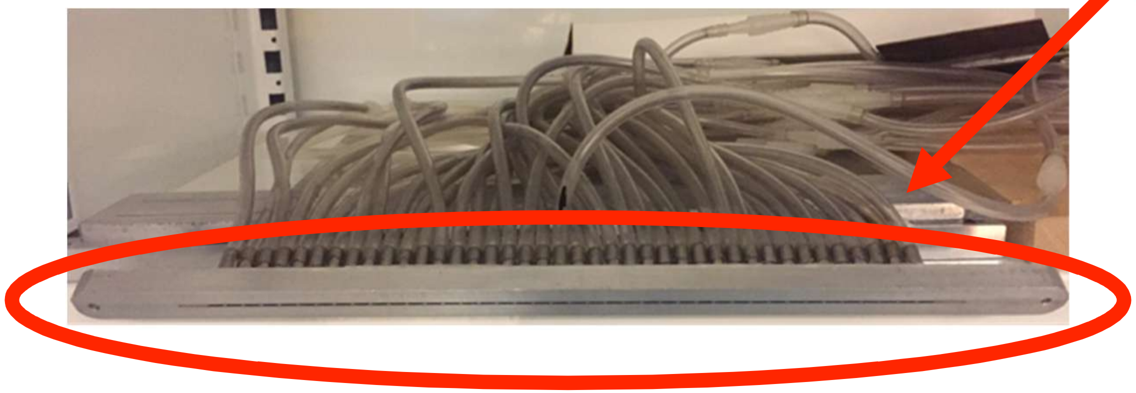


Fig. 4 Forcing field corresponding to the actuator model used here.

Disturbance generator

Disturbance generator





- Disturbance generated by a set of speakers

Plasma actuator

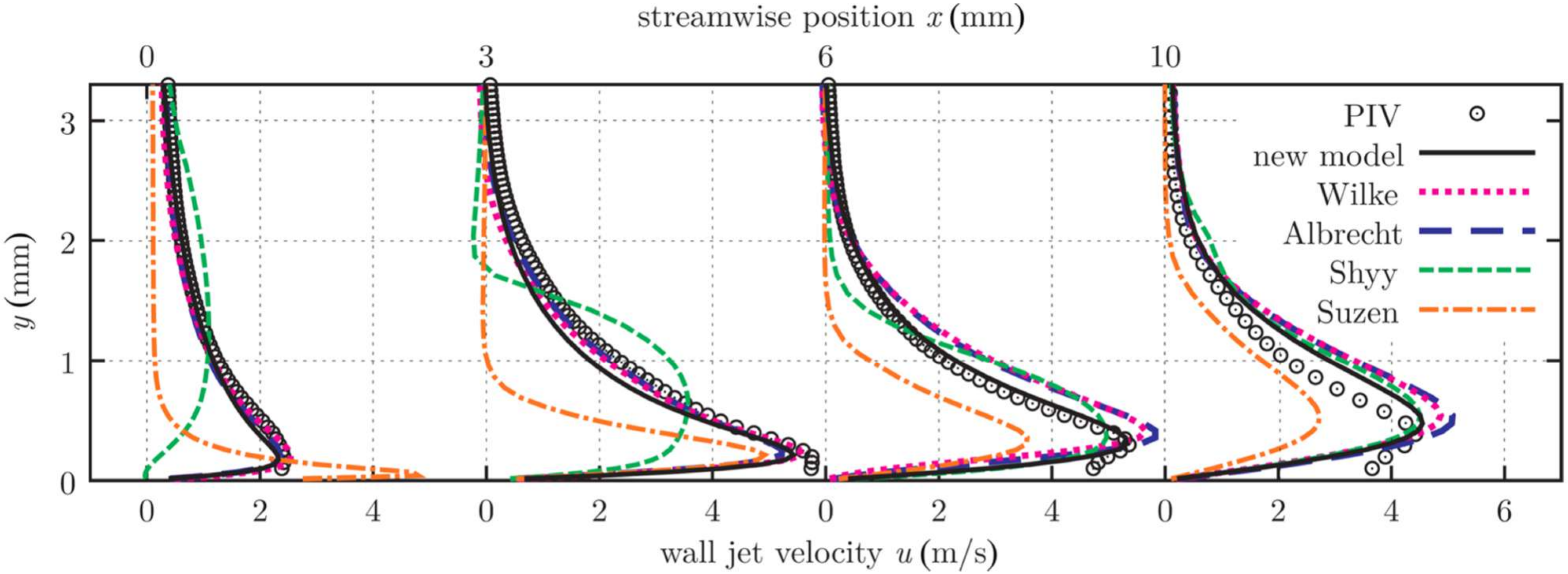
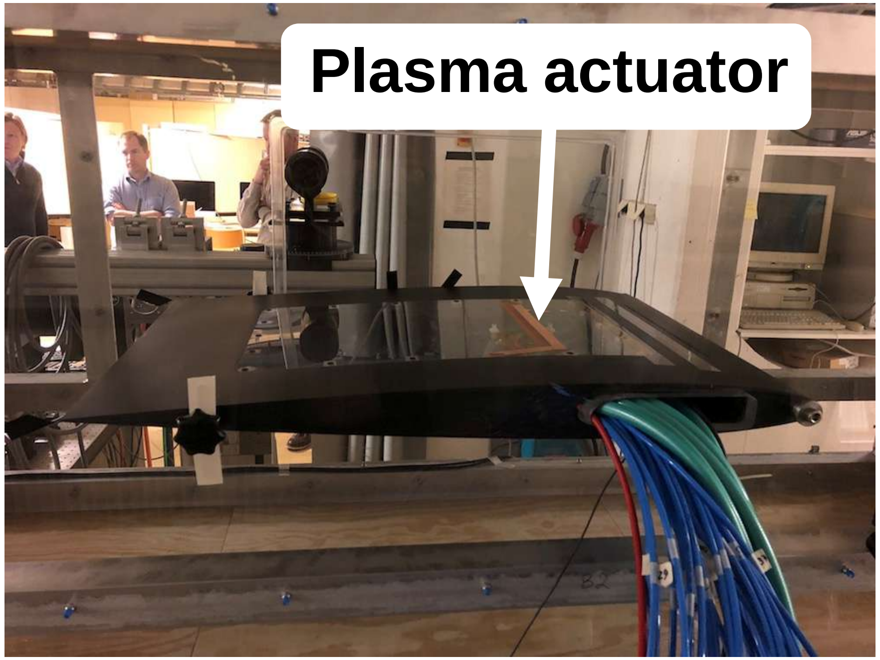


Fig. 33 "Experimentally and computationally obtained mean velocity profiles $u(y)$ at selected streamwise locations x; implemented models: Wilke [154] and Albrecht et al. [155], according to Shyy et al. [169] and Suzen et al. [170]; PIV data: Kriegseis [38]." (Reprinted with permission from Maden et al. [167]. Copyright 2012 by Imdat Maden.)

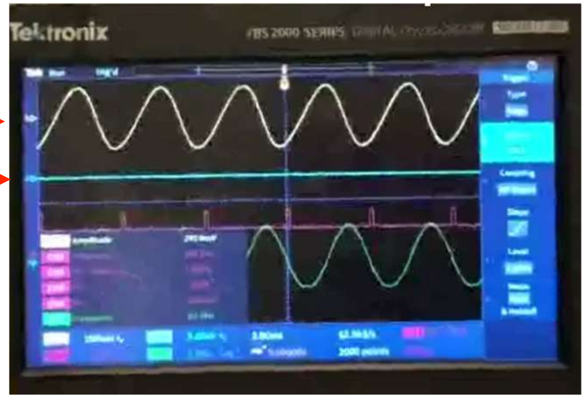
Experimental results



(KTH Lab: S. Mamidala, B. Fallenius, J. Fransson)

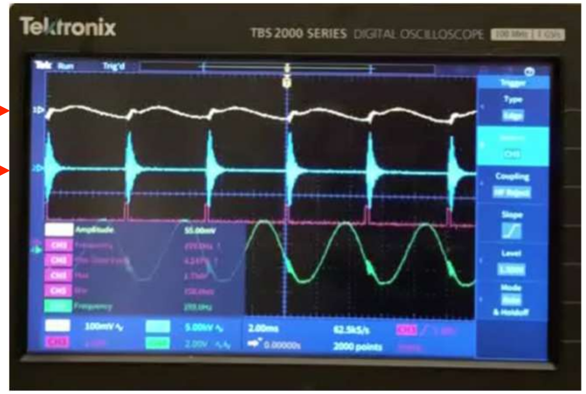
Disturbance

Actuator (off)



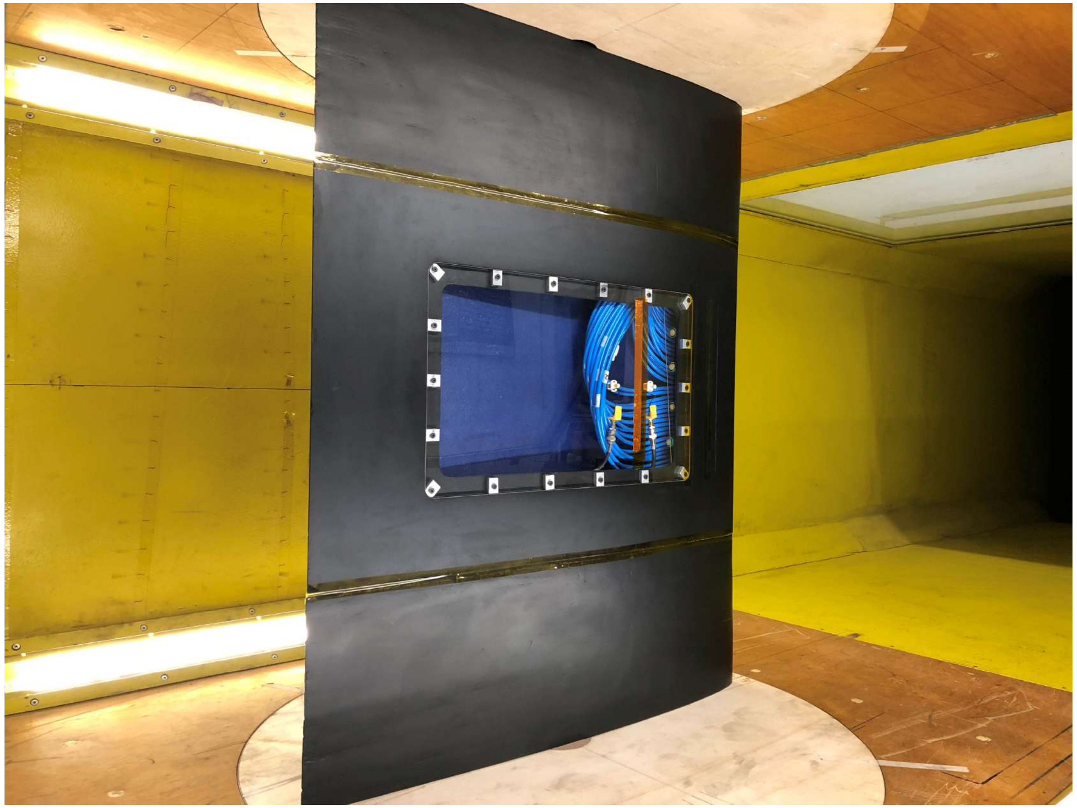
Disturbance

Actuator (on)



- Successful single frequency cancellation

Experimental setup

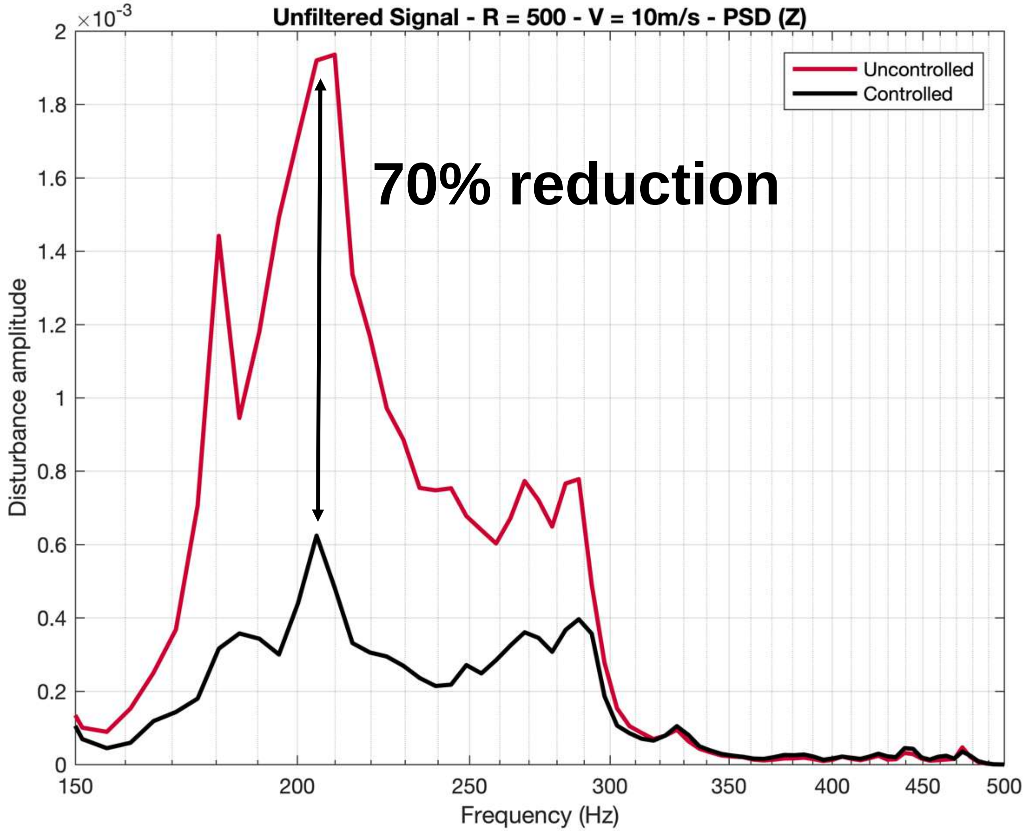


Larger open loop WT → Higher FST → More difficult control problem

- NACA0008 wing manufactured by SAAB (L. Hjelm, B. Roxberg) in the wind-tunnel of the Istituto Tecnologico de Aeronautics (Brazil)

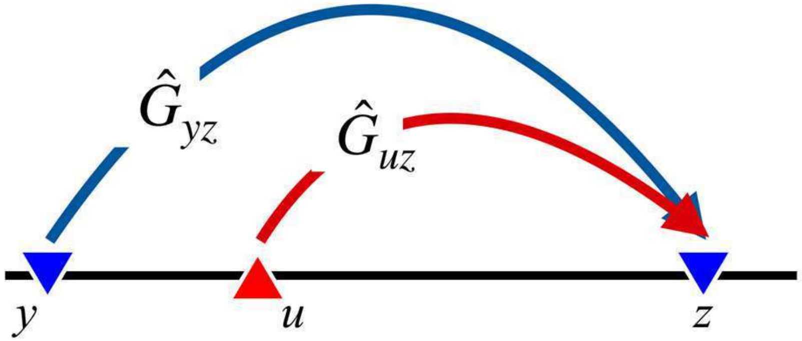
Experimental results

Broadband disturbance



- Successful closed-loop control of white noise perturbation in the wind-tunnel experiment

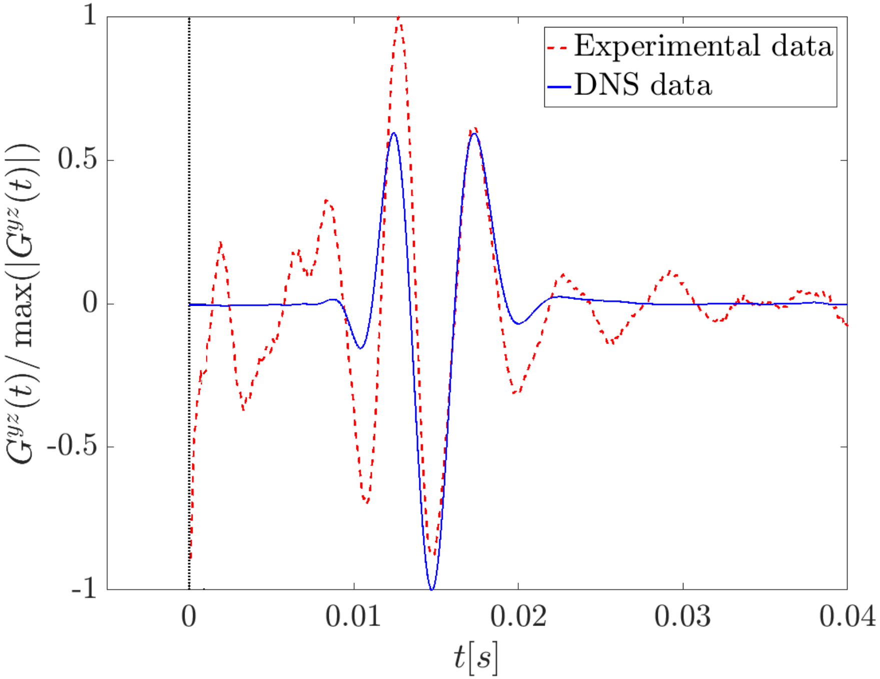
DNS vs Experiments

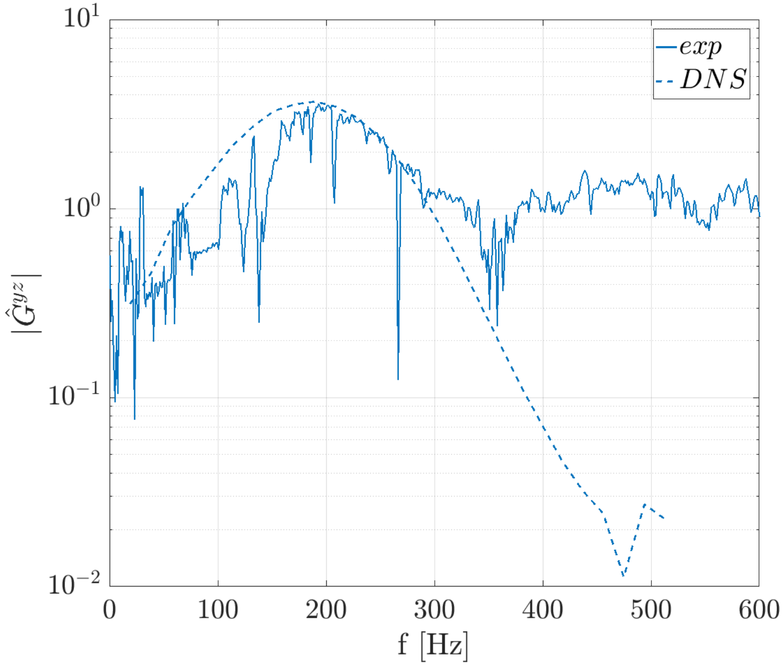


$$\hat{u}(\omega) = \hat{K}(\omega)\hat{y}(\omega)$$

$$\hat{K}(\omega) = \frac{\hat{G}^*_{uz}(\omega)\hat{G}_{yz}(\omega)}{\hat{R} + \hat{G}^*_{uz}(\omega)\hat{G}_{uz}(\omega)}$$

Need the transfer functions!





DNS vs Experiments

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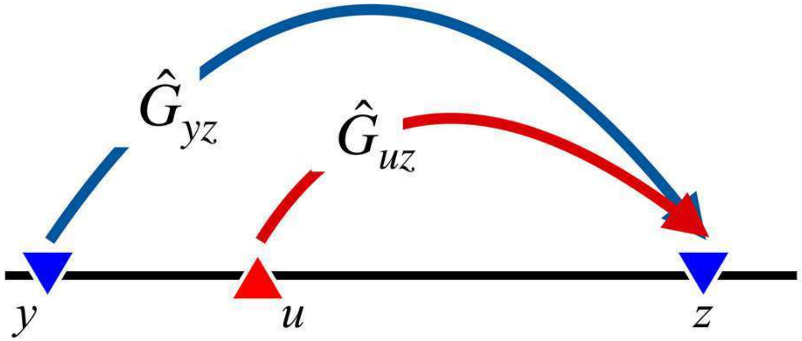

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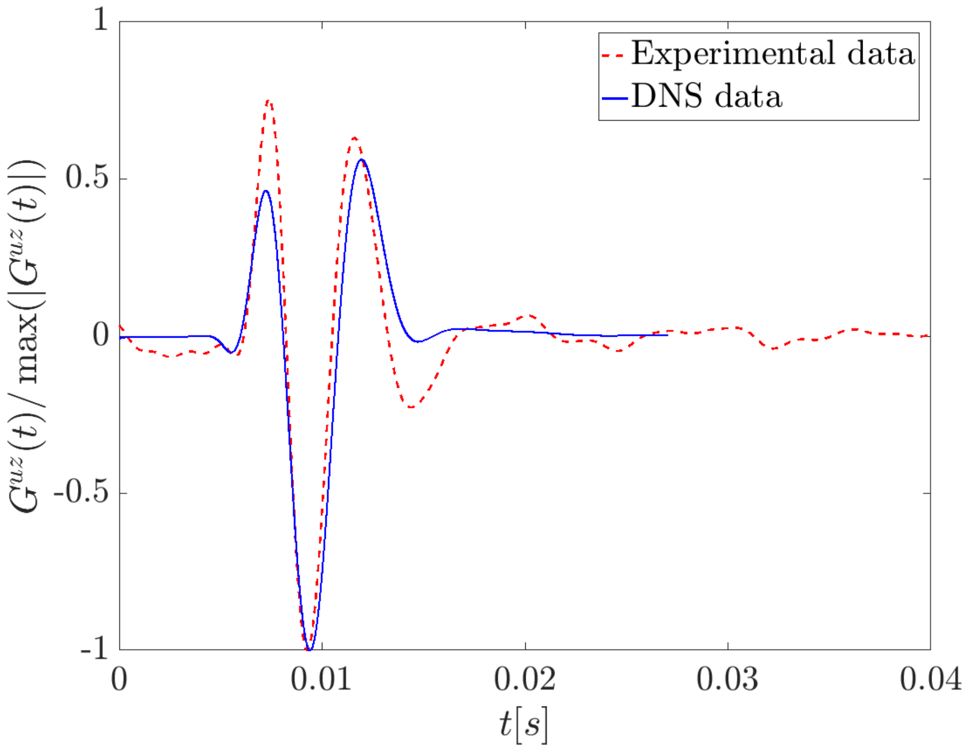
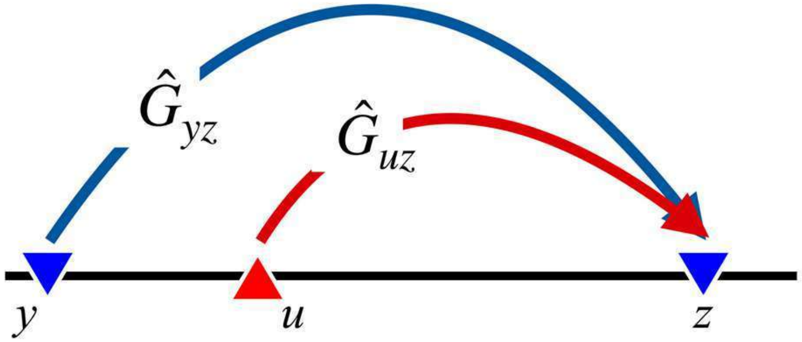


DNS vs Experiments



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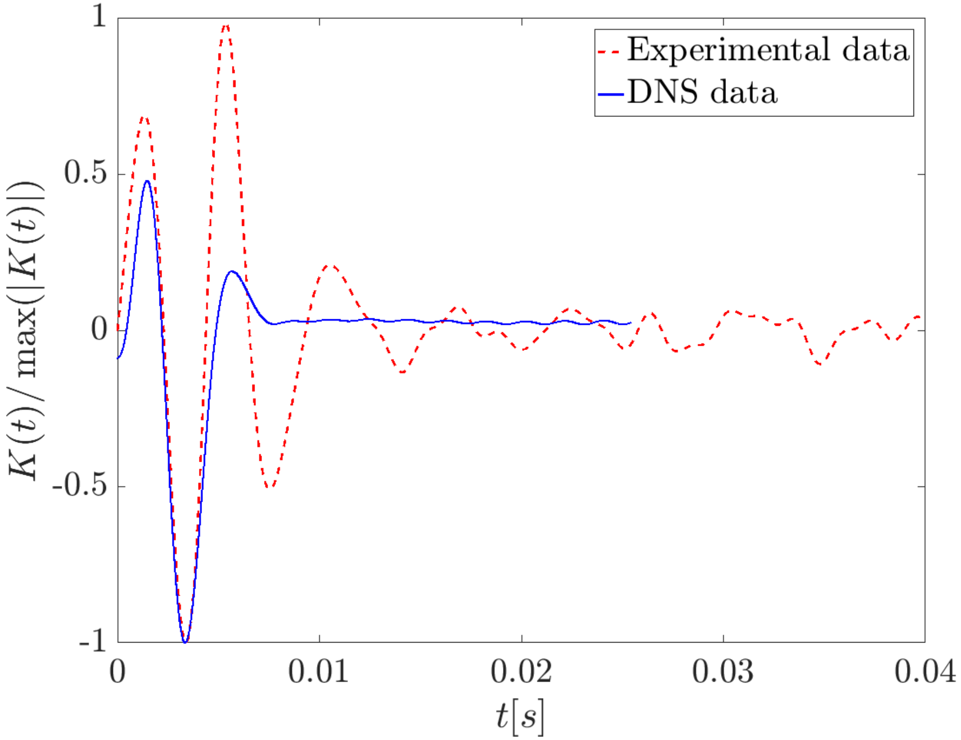
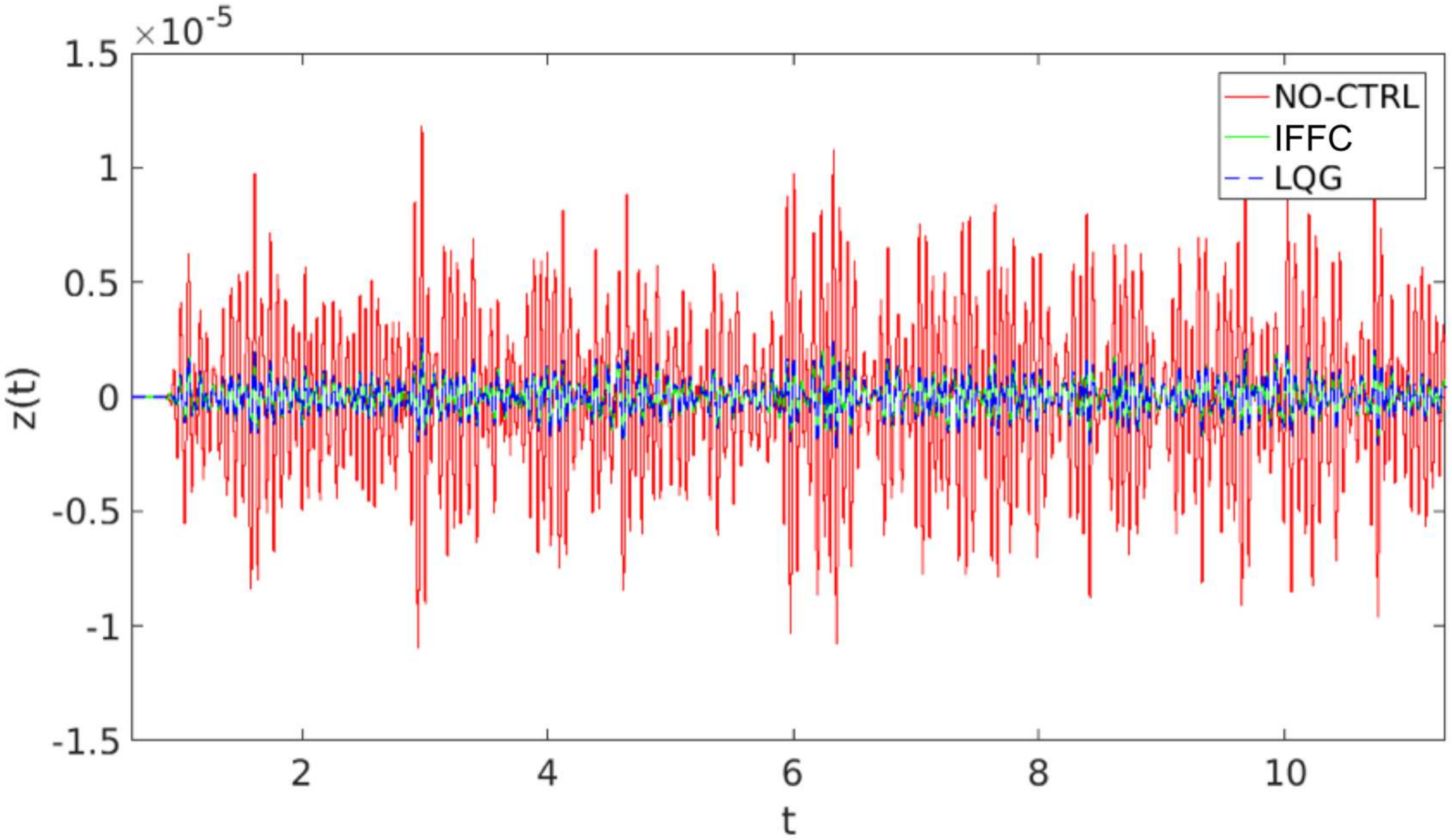
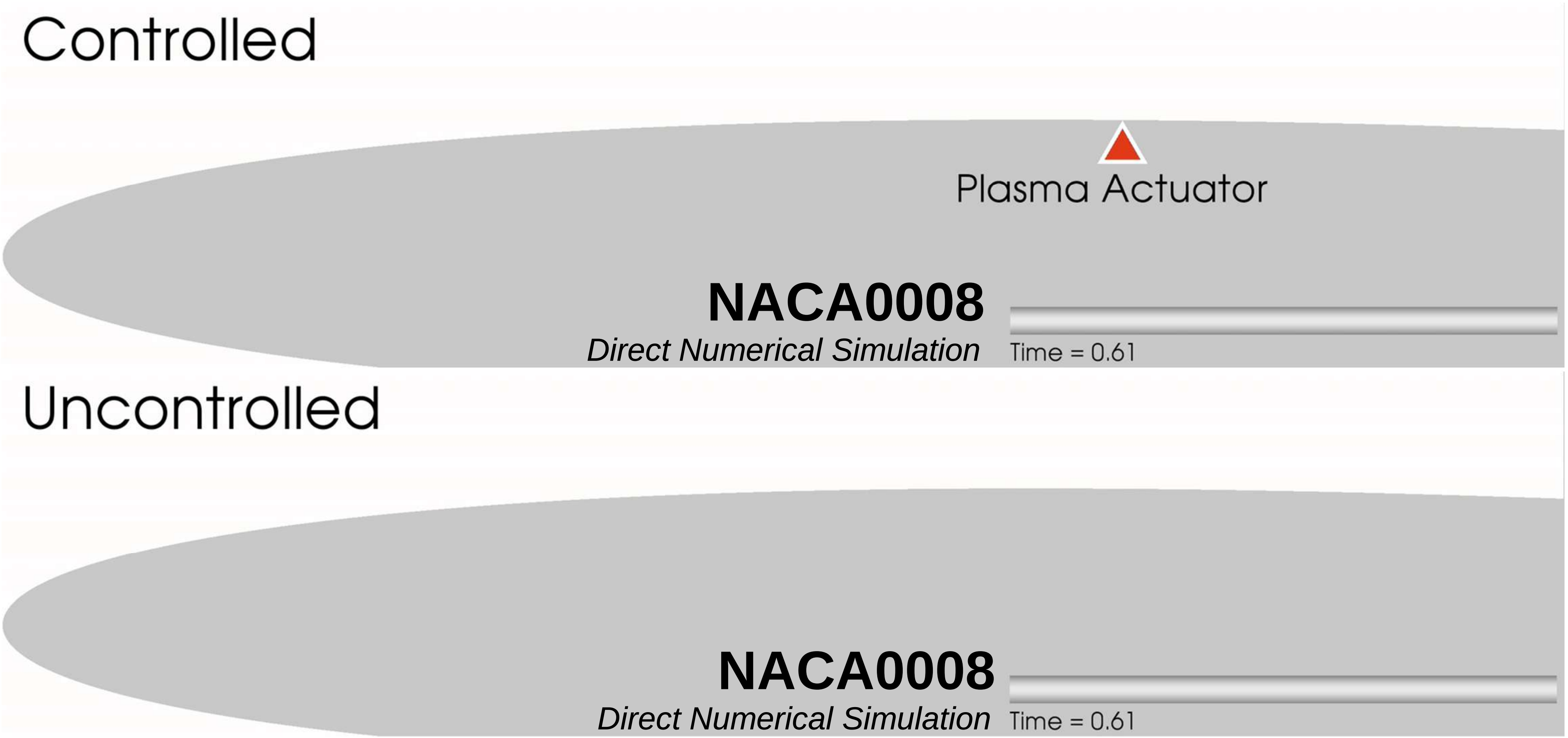


DNS results



- Successful closed-loop control of white noise perturbation in the direct numerical simulation

DNS results


Controlled
Plasma Actuator
NACA0008
Direct Numerical Simulation
Time = 0.61
Uncontrolled
NACA0008
Direct Numerical Simulation
Time = 0.61

Summary & Conclusions

- Successful closed-loop control of TS-waves achieved
- Direct numerical simulations predict well the wind-tunnel experiments
- Direct numerical simulations can be used as a virtual wind tunnel in addition to wind tunnel experiments to accelerate the design process