Karlsruhe Institute of Technology

Impulse Response in Turbulent Channel Flow

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Institute of Fluid Mechanics istm

EUROPEAN DRAG REDUCTION AND FLOW CONTROL MEETING, 3 - 6 APRIL 2017, MONTE PORZIO CATONE (ROMA), ITALY

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Motivation

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Impulse Response Features

It describes the Input-Output relationship of a dynamic system.

- Perturbation propagation
- Flow control application (plasma actuators)
- Insights for development and testing of turbulent models[1]

Background

M. Jovanović and B. Bamieh, *Componentwise energy amplification in channel flows* - J. Fluid Mech., 2004

Impulse response for linearized laminar channel flow

Goal

Extend Jovanović's work and provide the impulse response in the turbulent case

1) S. Russo, P. Luchini - J. Fluid Mech., 2016

Jovanović 2004

Description

Impulse response to volume force $\mathcal{H}_{ij}(k_x, y, k_z, \omega)$

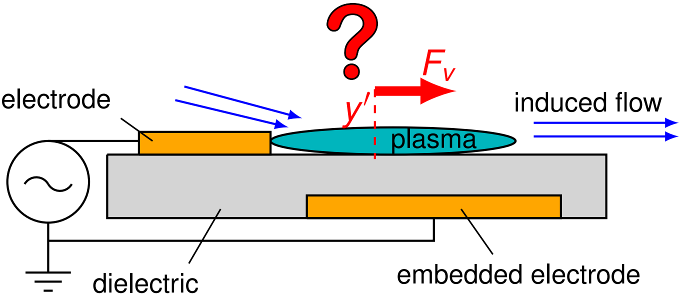
- linearized laminar base flow
- results averaged in the wall-normal direction
- forcing uniformly applied among the channel height

Current work

Impulse response to volume force $\mathcal{H}_{ij}(x, y, z, t; y_f)$

- turbulent base flow (DNS)
- physical space and time evolution
- influence of the wall-normal distance of the forcing y_f

Plasma Actuators



DBD configuration

Impulse Response

1D definition:

$$u(t) = \int \mathcal{H}(t - t')f(t)dt'$$

Impulse response $\mathcal{H}$ (fluid dynamics)

Relationship between the body forcing input $\mathbf{f}(\mathbf{x}, t)$ and the velocity output $\mathbf{u}(\mathbf{x}, t)$:

$$\mathbf{u}_i(\mathbf{x}, t) = \int \mathcal{H}_{ij}(\mathbf{x} - \mathbf{x}', t - t')\mathbf{f}_j(\mathbf{x}', t)d\mathbf{x}'dt'$$

Impulse Response Measurement

Three possible techniques:

Impulse Response

- ✓ easy implementation
- ✗ linear response ⇒ small perturbation ⇒ small S/N ratio

Frequency Response [1]

- ✓ distributed force
- ✗ only one space-time frequency at once

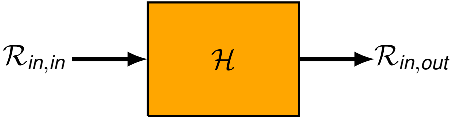
Input-Output correlation[2]

- ✓ tested for the wall blowing/suction input
- ✓ more homogeneous force distribution, all time-space frequency at once

1) A.K.M.F. Hussain, W.C. Reynolds - J. Fluid Mech., 1970
2) P. Luchini, M. Quadrio, S. Zuccher - Phys. Fluids, 2006

Impulse Response Measurement

Input-Output correlation[1] $\mathcal{R}_{in,out}$



$$\mathcal{R}_{in,out}(t) = \int \mathcal{H}(t-\tau)\mathcal{R}_{in,in}(\tau)d\tau$$

White noise input:

$$\mathcal{R}_{in,in}(\tau) = \delta(\tau)$$

$$\Rightarrow \mathcal{R}_{in,out}(\tau) = \mathcal{H}(\tau)$$

1) P. Luchini, M. Quadrio, S. Zucchér - Phys. Fluids, 2006

3D Mean Impulse Response

DNS of Turbulent channel flow at $Re = 150$

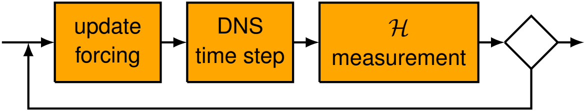
Volume force applied at a certain wall normal distance y_f

$$f_j(\alpha, y, \beta, t) = \epsilon \mathfrak{f}_j(\alpha, \beta, t)\delta(y - y_f)$$

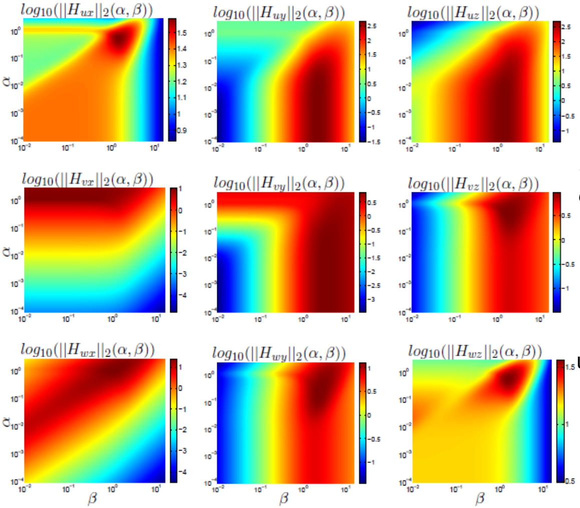
Measurement formulation

$$\mathcal{H}_{ij}(\alpha, y, \beta, \mathcal{T}; y_f) = \frac{\langle u_i(\alpha, y, \beta, t)\mathfrak{f}_j^*(\alpha, \beta, t - \mathcal{T})\rangle}{\epsilon^2}$$

- 4+1 variables describe the impulse response
- $\mathcal{H}_{ij}$ is a 3x3 tensor
- phase-locked averaged (mean) impulse response



Results from Jovanović's work



H_2 norm: *ensemble average energy density*

$$\forall y_f \quad \|\mathcal{H}\|_2^2 \equiv \int_0^H \int_0^\infty \|\mathcal{H}(\alpha, y, \beta, t)\|_{HS}^2 dtdy$$

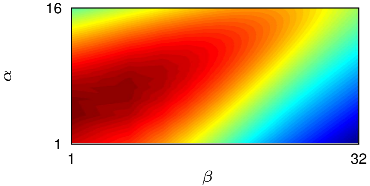
uniform forcing across the height

M. Jovanovic, B. Bamieh - J. Fluid Mech., 2004

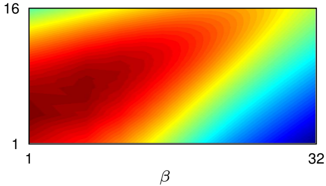
Validation

Response component $\mathcal{H}_{ux}$ with laminar flow at $Re_P = 2000$.

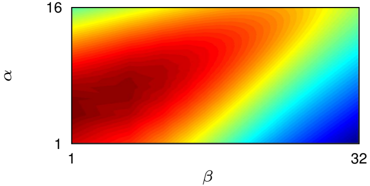
Jovanović & Bamieh



Direct Impulse



Input-Output correlation



Channel resolution:

$L_x = 4\pi H$, $L_z = 2\pi H$, 128x100x128

Response resolution:

64x100x64

with 100 time step from $\tilde{t} = 0$ to $\tilde{t} = 100$

Validation

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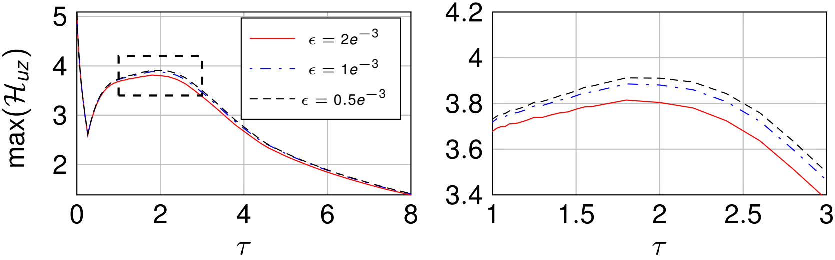
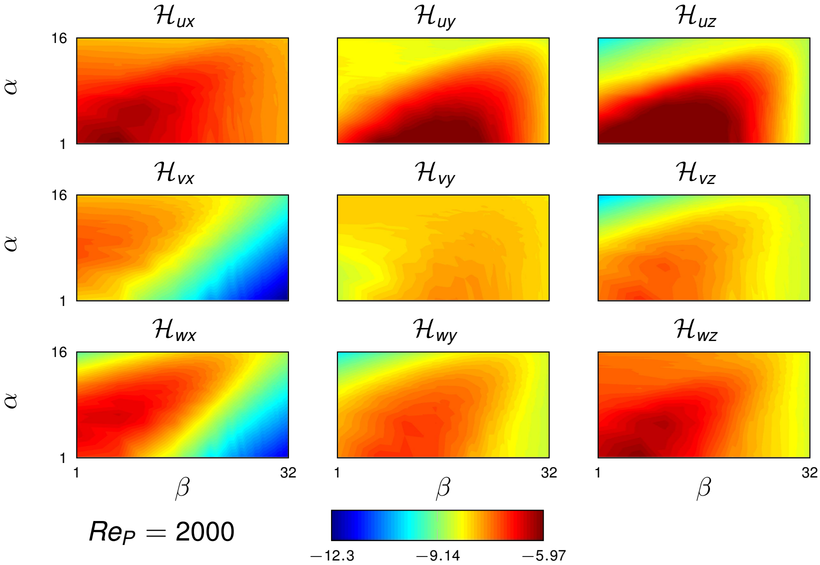
Linearity test

$$f_j(\alpha, y, \beta, t) = \epsilon \mathfrak{f}_j(\alpha, \beta, t)\delta(y - y_f)$$



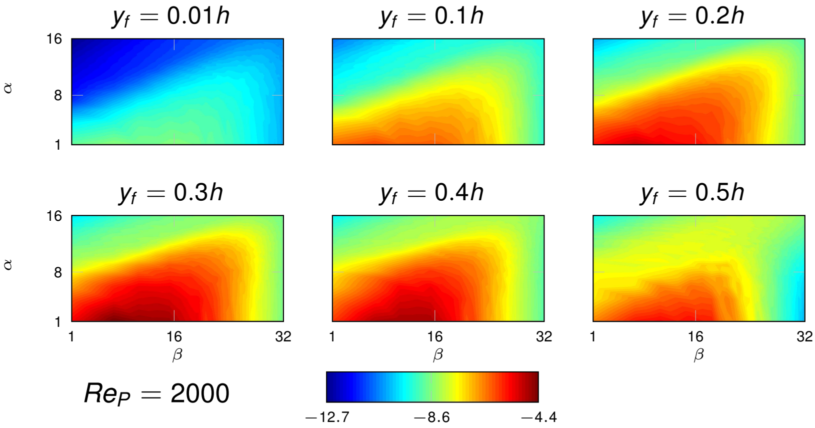
Forcing distance: $y_f = 0.1H$

H_2 Norm, Laminar case

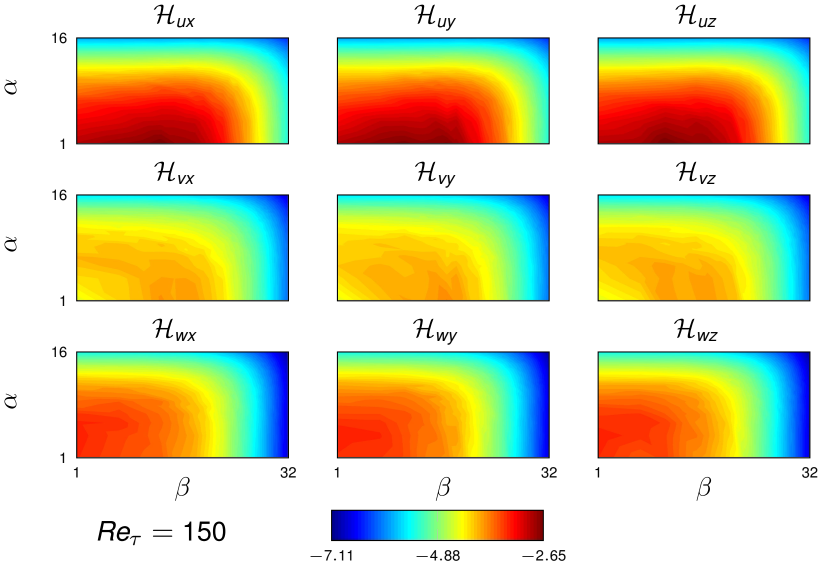


Influence of the forcing distance y_f

Response component $\mathcal{H}_{uz}$

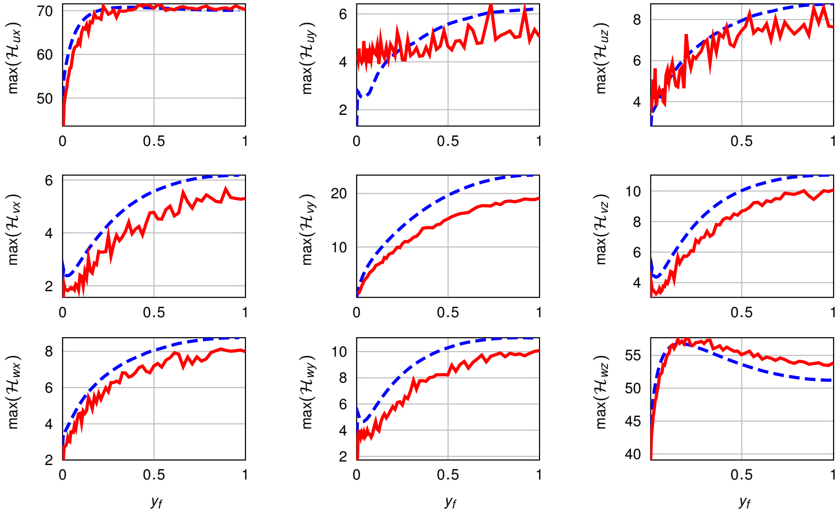


H_2 Norm, Turbulent case



$Re_\tau = 150$

Maxima of $\mathcal{H}_{ij}$ vs. forcing distance y_f



(- - -) Laminar, (——) Turbulent

Conclusion & Outlook

Conclusion

- Successful validation of new response measurement technique.
- First turbulent characterization almost done (just averaging).
- Analysis of the $||\mathcal{H}||_2$ show that $\mathcal{H}_{uy}$ and $\mathcal{H}_{uz}$ are the most influent components.
- Influence of the forcing wall-normal distance.

Outlook

- Further averaging turbulent simulations.
- Response measurements at higher Reynolds numbers.

Thank you for your attention!

Special thanks to Mihailo Jovanović.

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