DNS of Roughness-Induced Transition in the Boundary Layer of a Hypersonic Spherical Forebody

Antonio Di Giovanni

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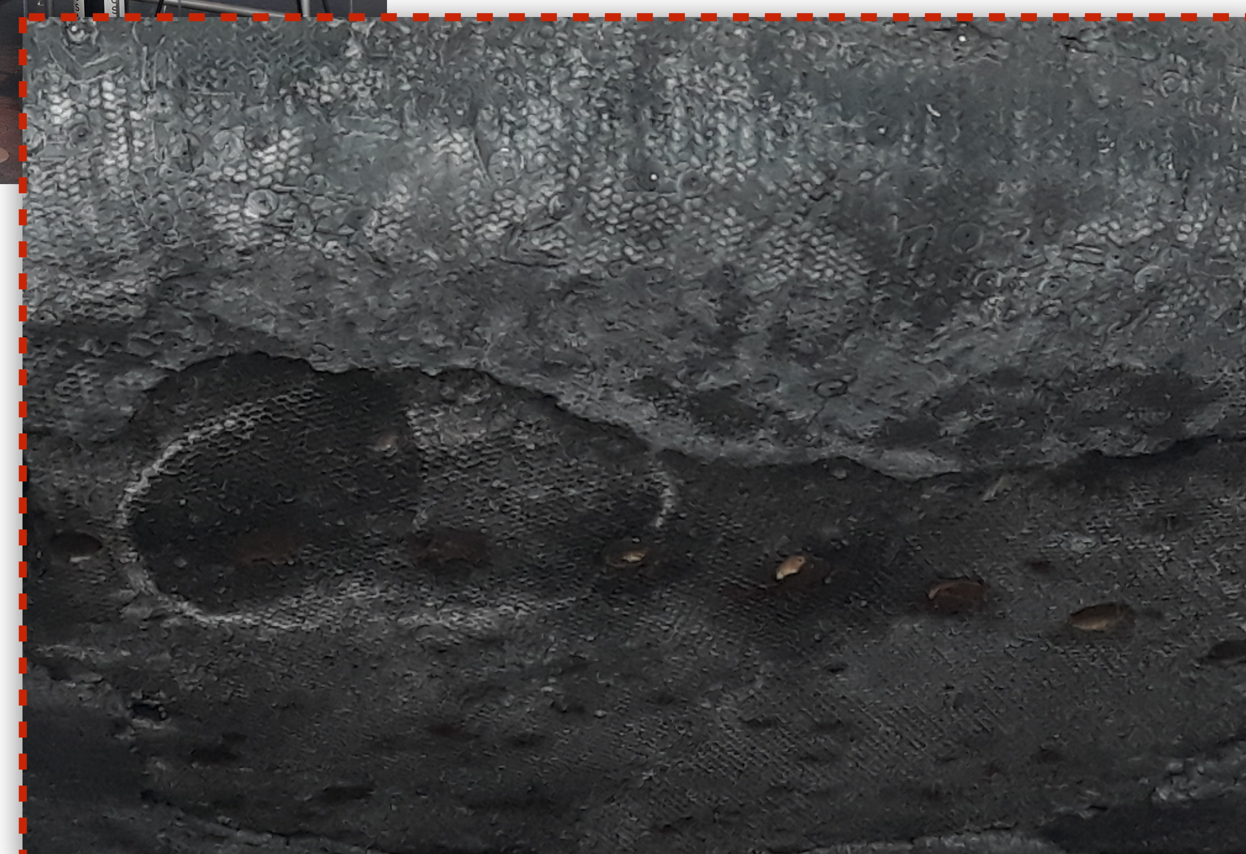
Technical University of Munich

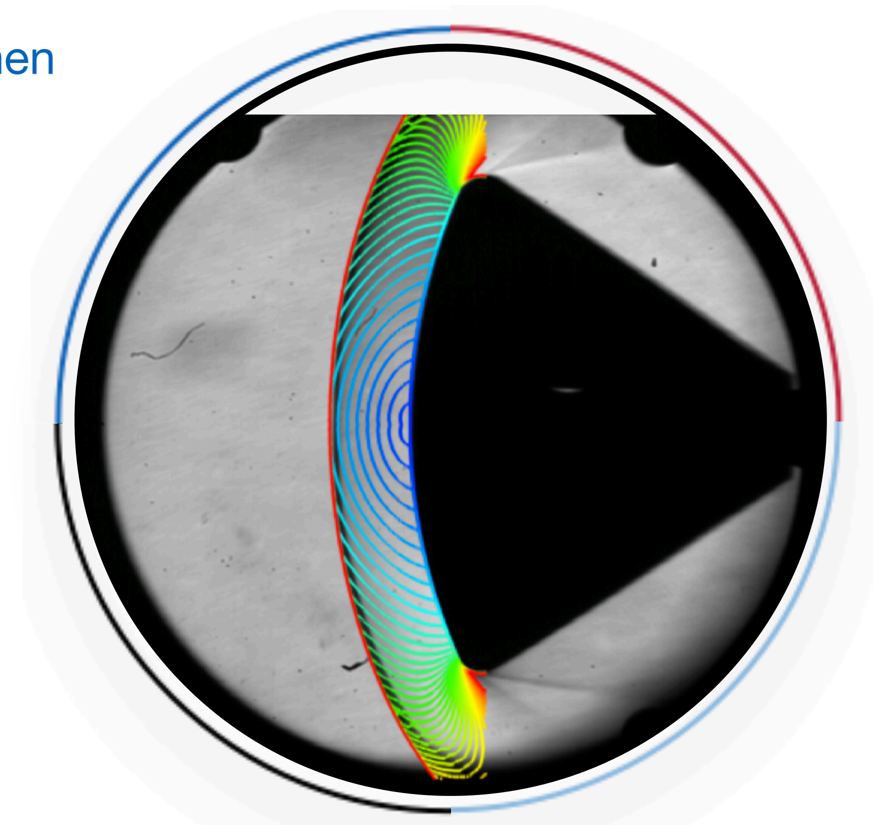
Motivation

Apollo 12 Command Module,
Virginia Air & Space Center



Project: Transition on Capsule Configurations

Technische Universität München



Technische Universität Braunschweig

DLR

RWTH AACHEN UNIVERSITY

Project: Transition on Capsule Configurations

Technische Universität München

- DNS
- High-Temperature Gas Effects

Technische Universität Braunschweig

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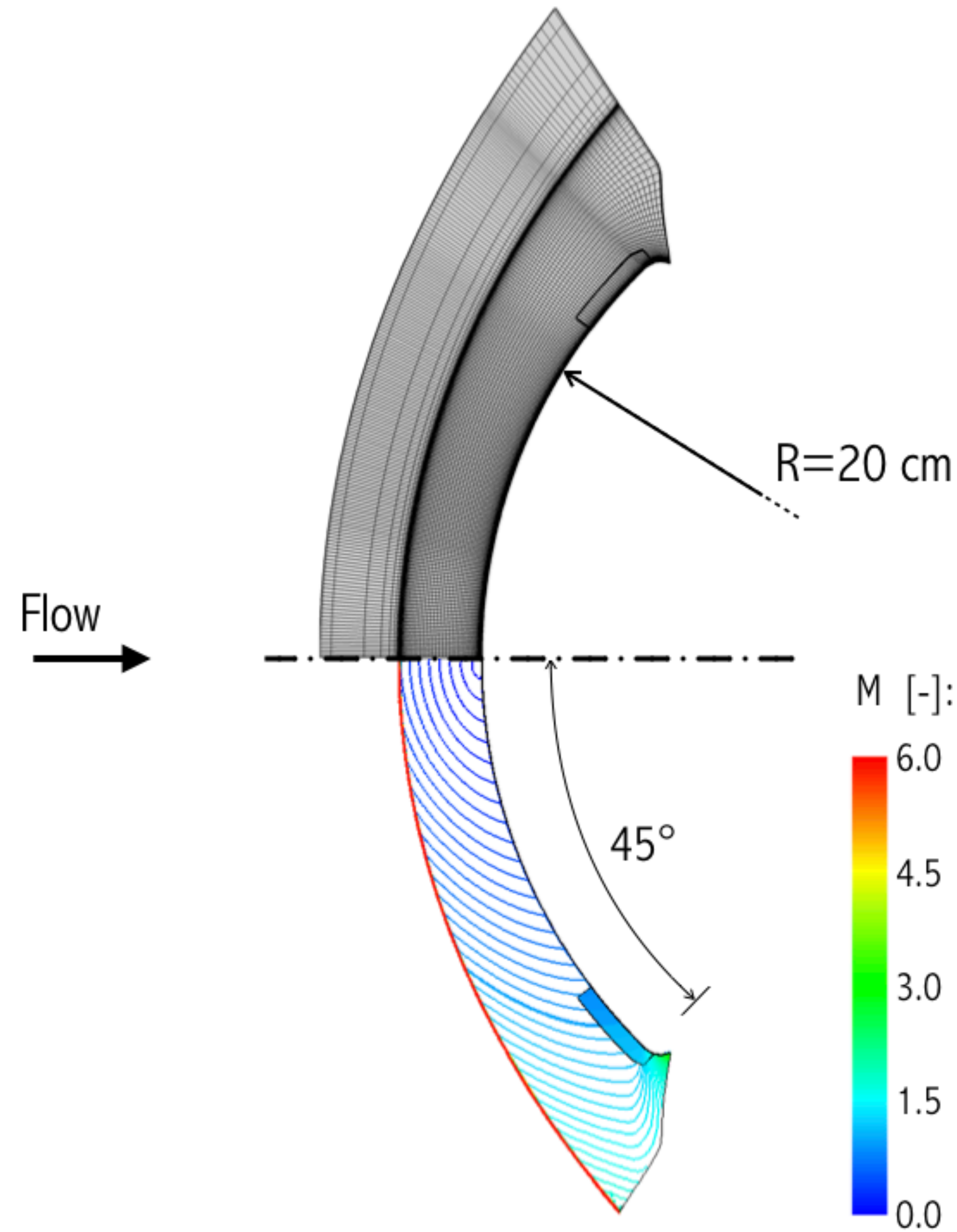
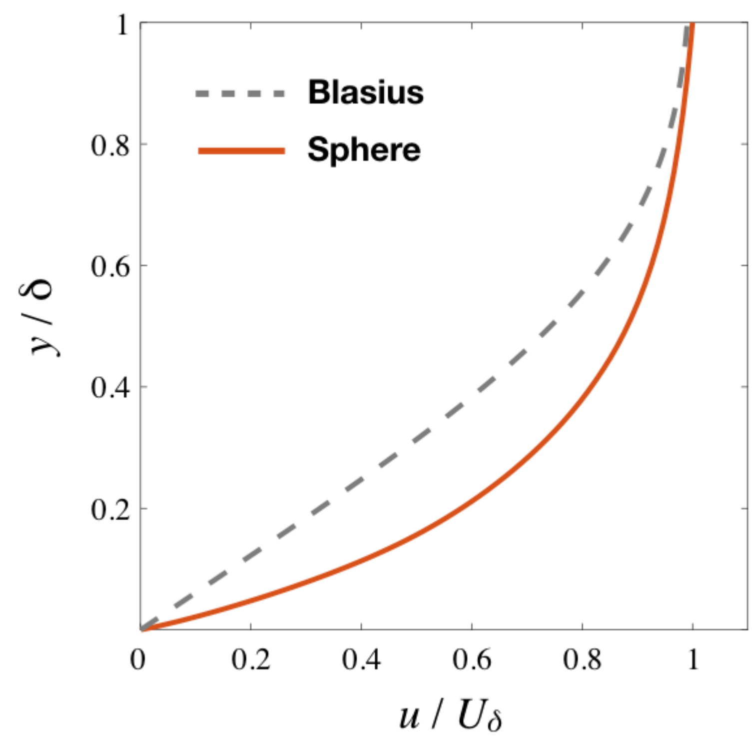
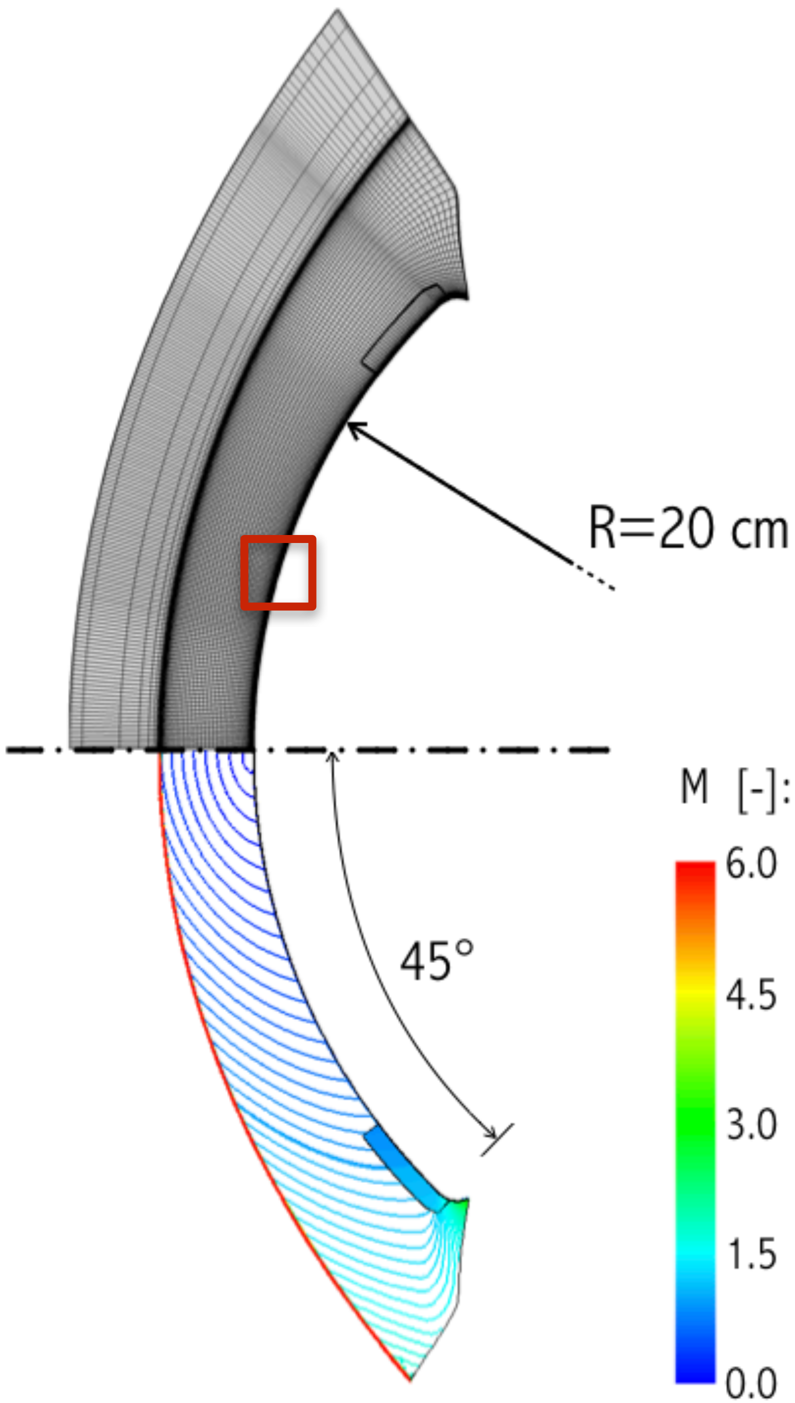
Analysis of the Smooth Configuration



Analysis of the Smooth Configuration

1st Mode: extremely accelerated boundary layer
—> STABLE





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Crossflow: absence of spanwise velocity component
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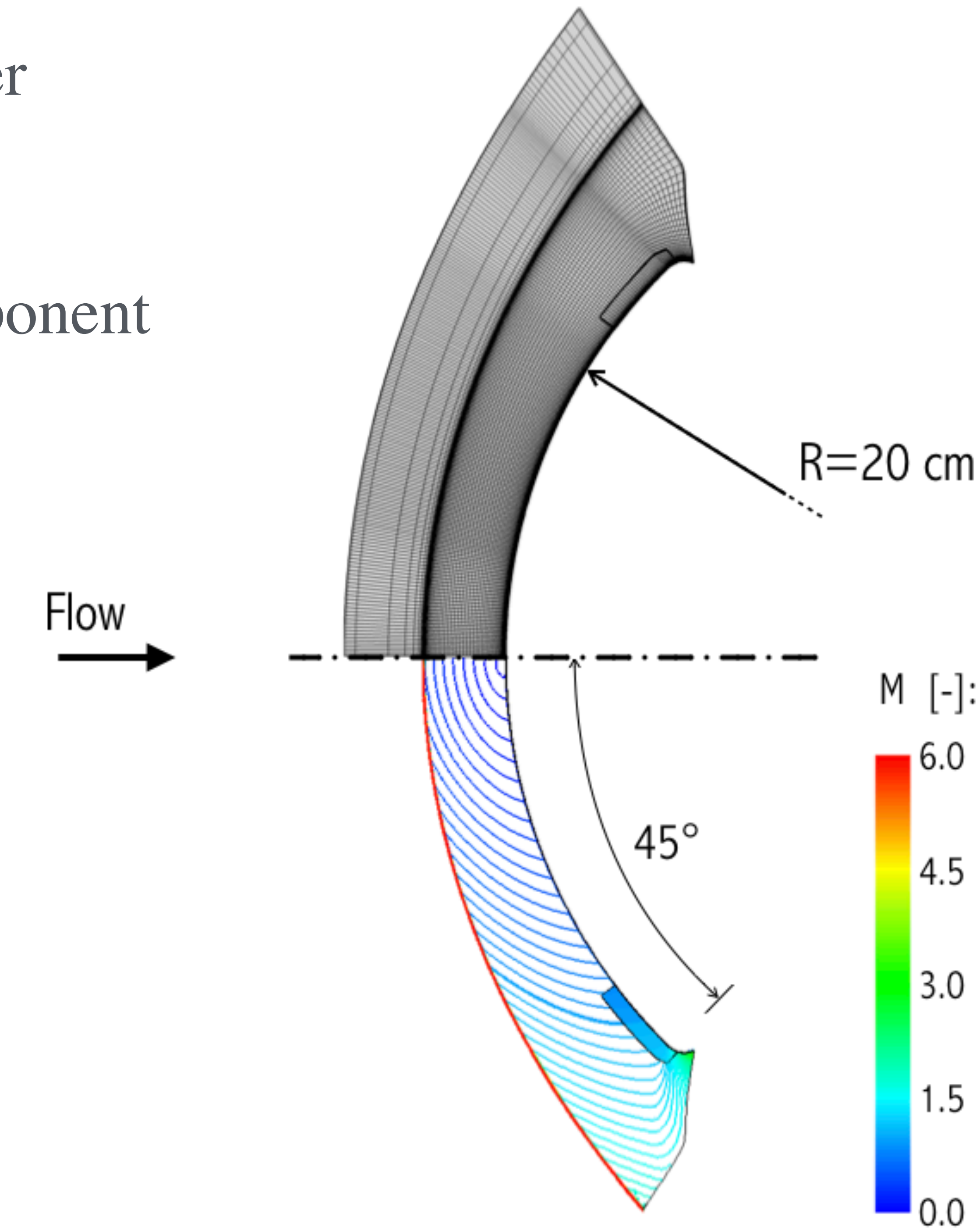

Analysis of the Smooth Configuration

1st Mode: extremely accelerated boundary layer
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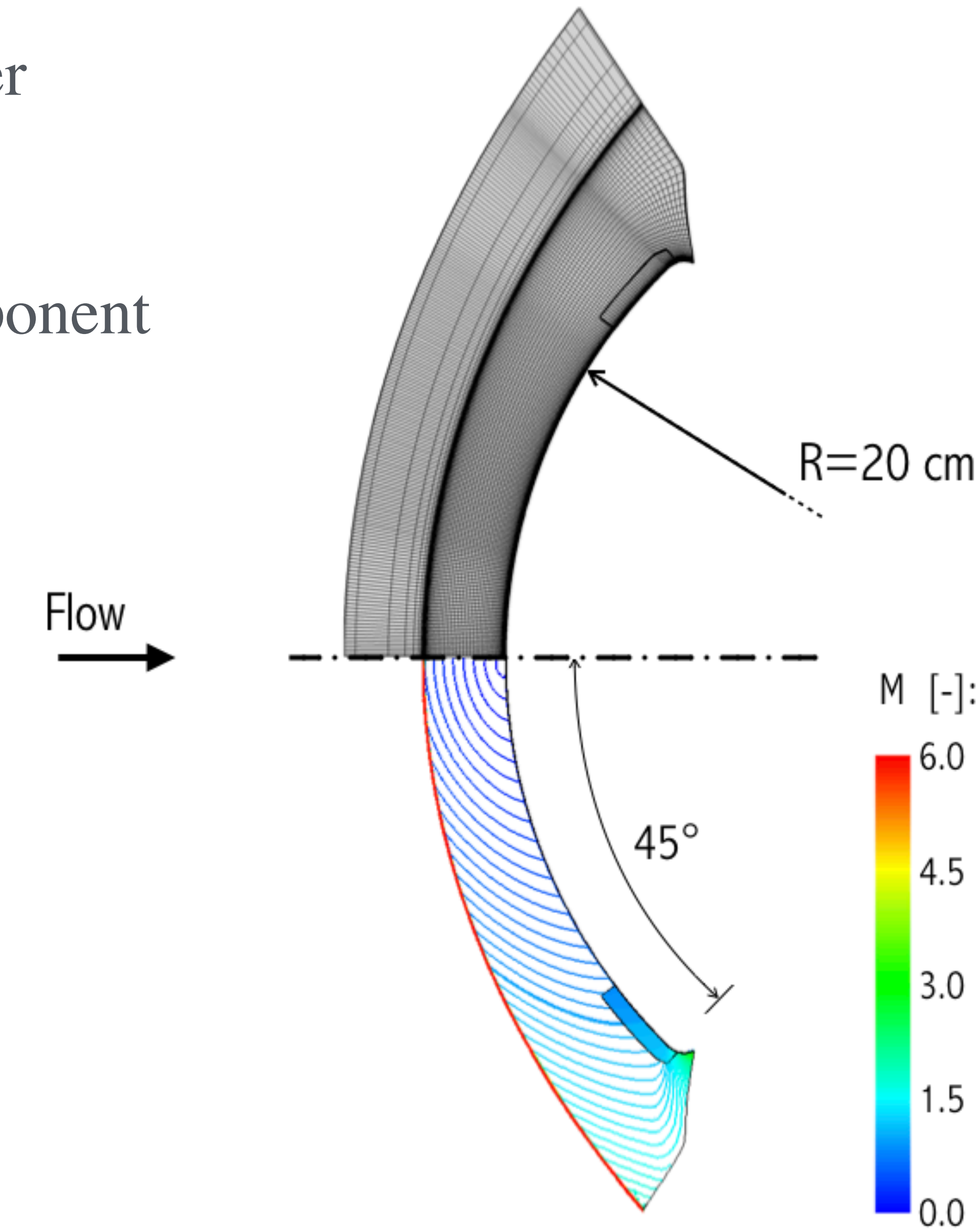

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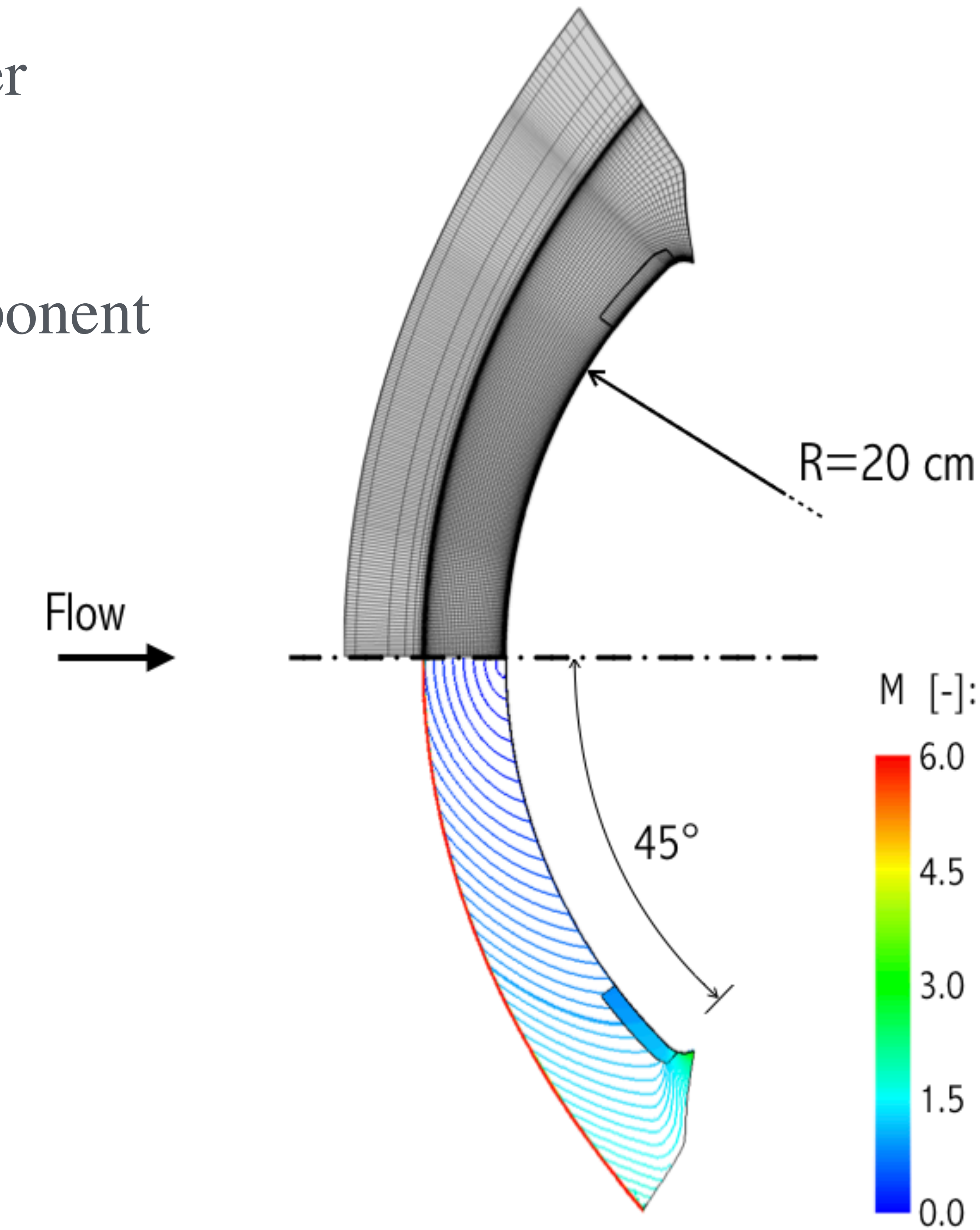
Transient Growth: *N*-factors < 3[1]
—> NEGLIGIBLE



[1] Hein, Theiss, Di Giovanni, Stemmer, Schilden, Schröder, Paredes, Choudhari, Li, Reshotko,: "Numerical Investigation of Roughness Effects on Transition on Spherical Capsules", *J. Spacecraft and Rockets,* 2018 (accepted)

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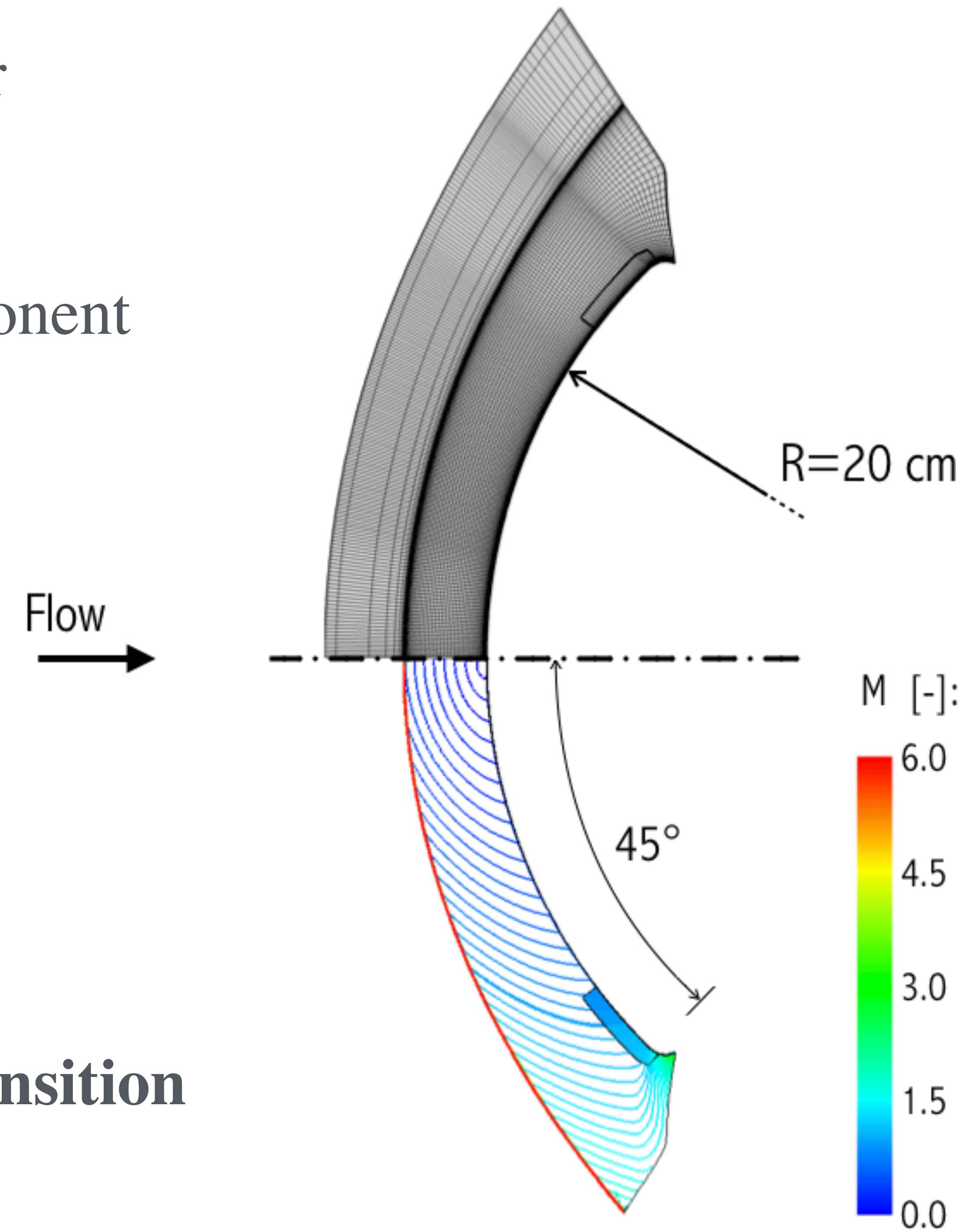
—> Roughness-induced transition



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Agenda

I. Wind-tunnel conditions ($M = 5.9$)

- Spanwise periodic roughness elements
- Random distributed roughness
  - Base Flow
  - Stability Analysis

II. Re-entry conditions ($M = 20$)

- Random distributed roughness
  - Base Flow
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Agenda

I. Wind-tunnel conditions ($M = 5.9$)

Spanwise periodic roughness elements

Random distributed roughness

Base Flow

Stability Analysis

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Random distributed roughness

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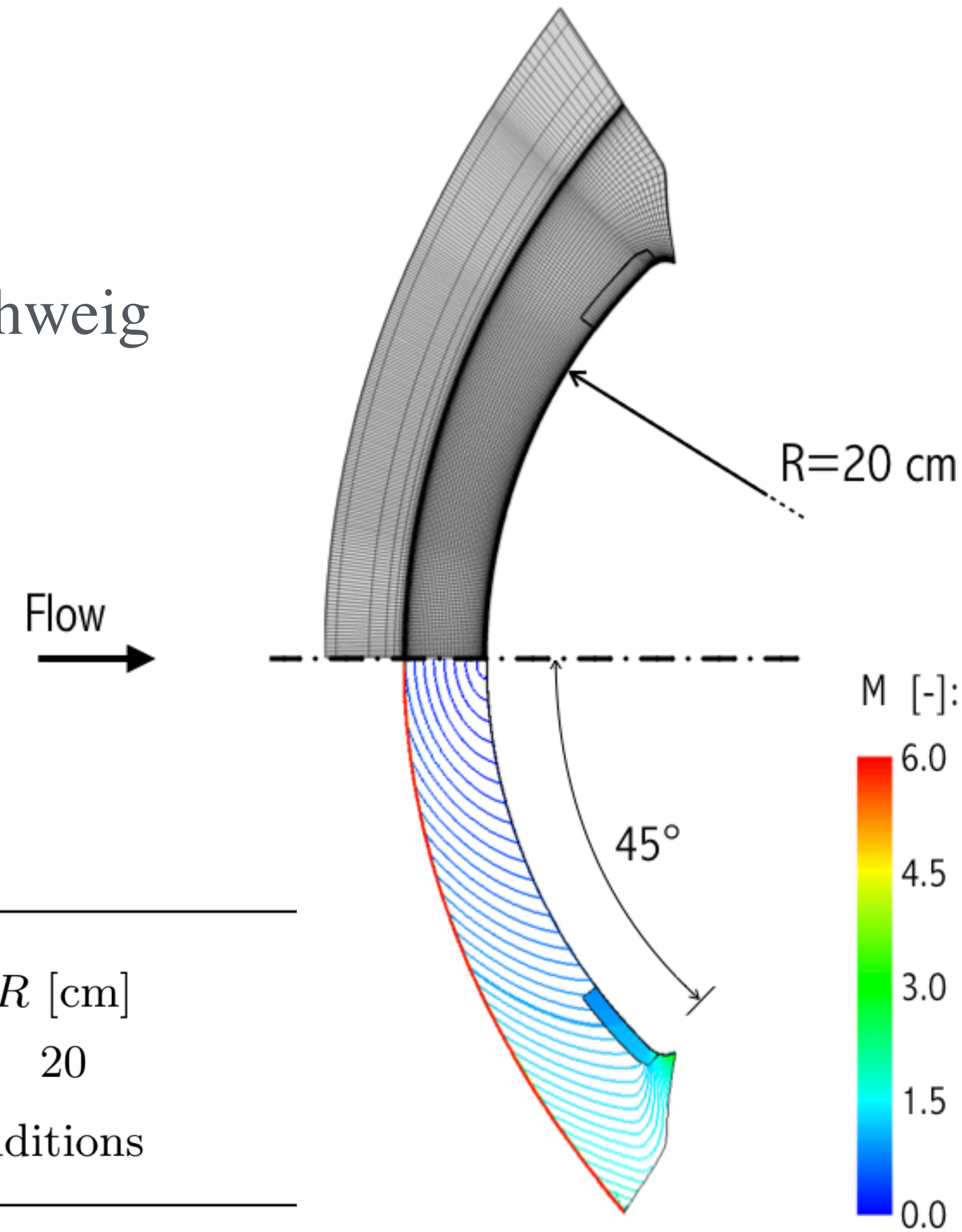
Stability Analysis

Geometry and Freestream Conditions

Geometry: capsule-like hemisphere

Conditions: Hypersonic Ludwieg tube Braunschweig (HLB)

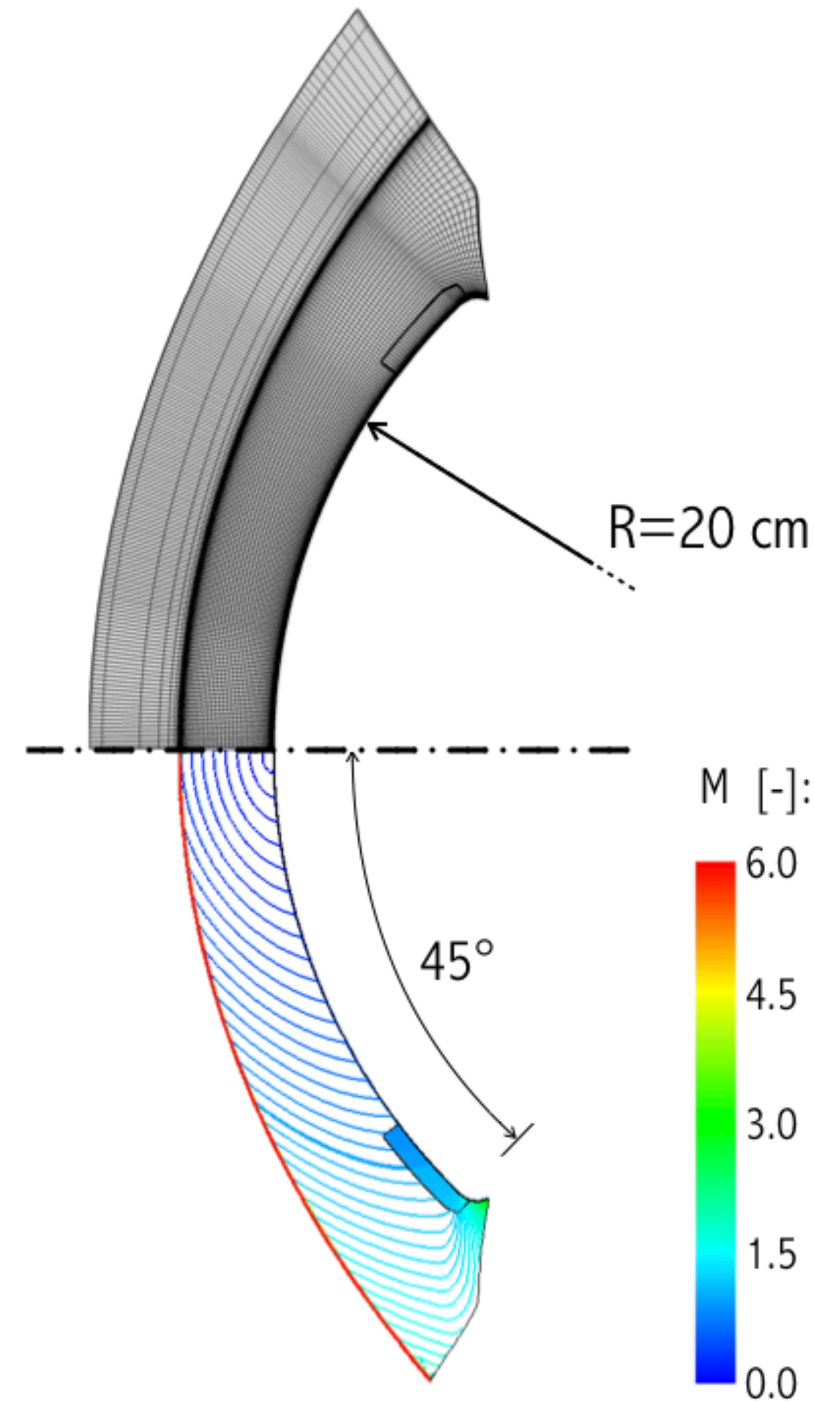
Gas model: ideal gas



Medium	M	T_0 [K]	T_w [K]	Re_∞ [1/m]	R [cm]
Air	5.9	470	295	$18 \cdot 10^6$	20

TABLE 1. Simulation parameters - windtunnel conditions

Analysis of a “simple” Roughness



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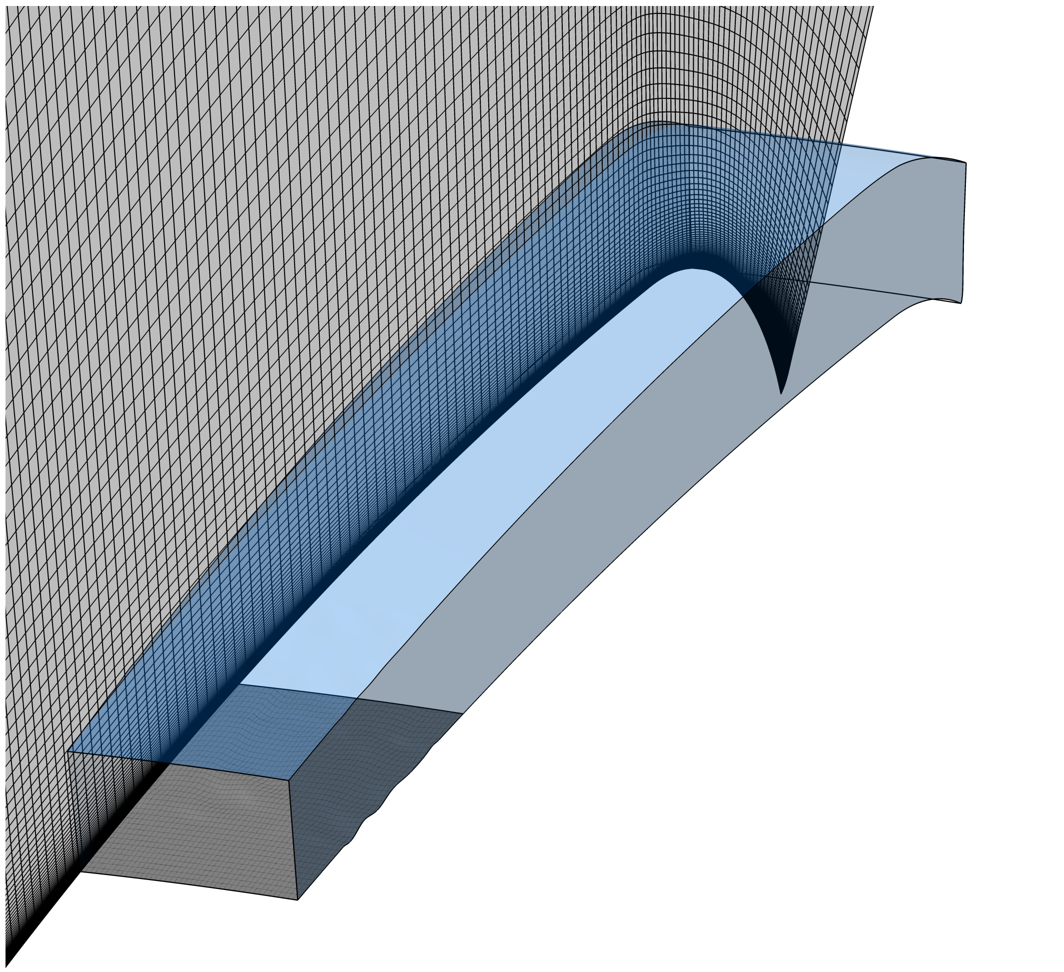

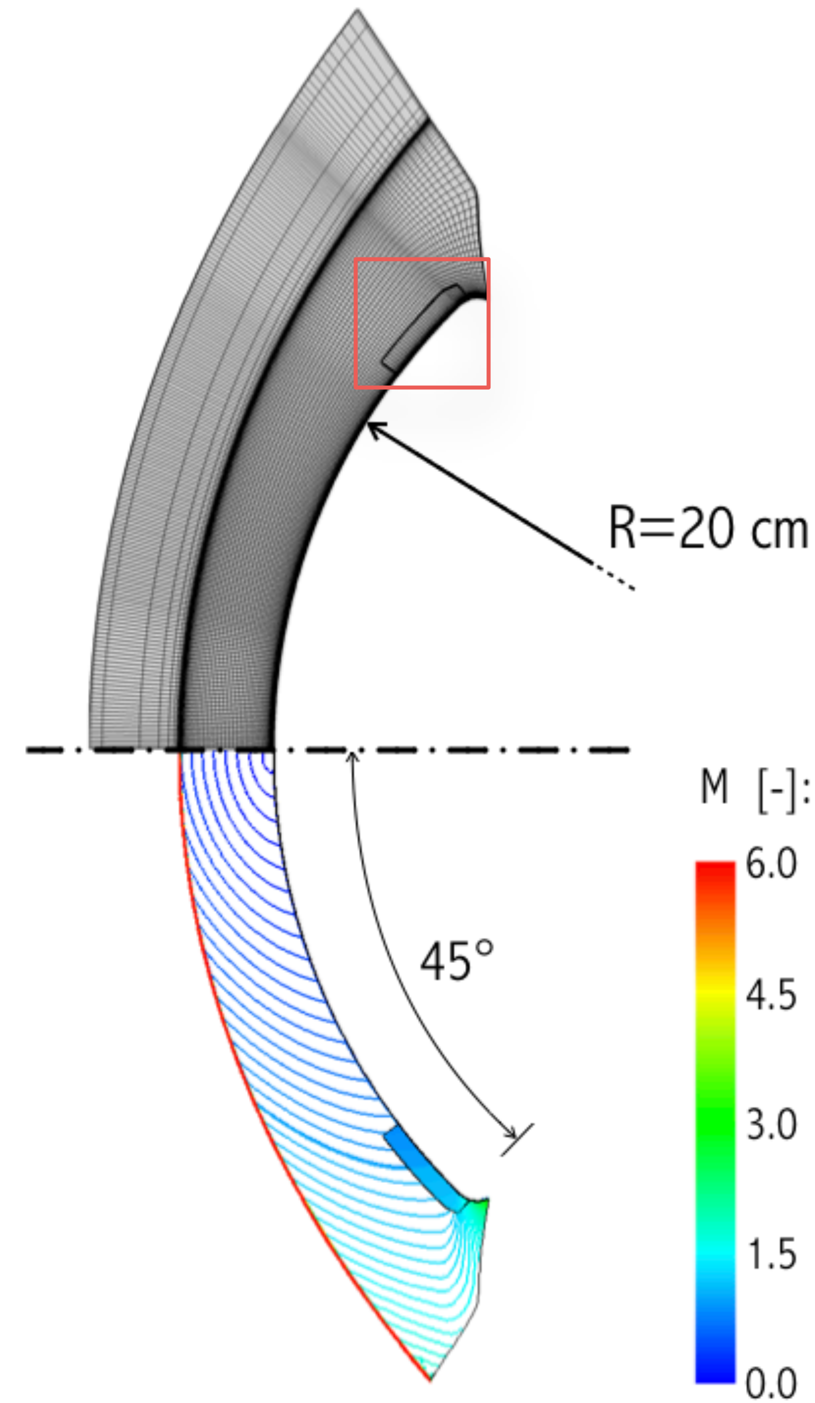

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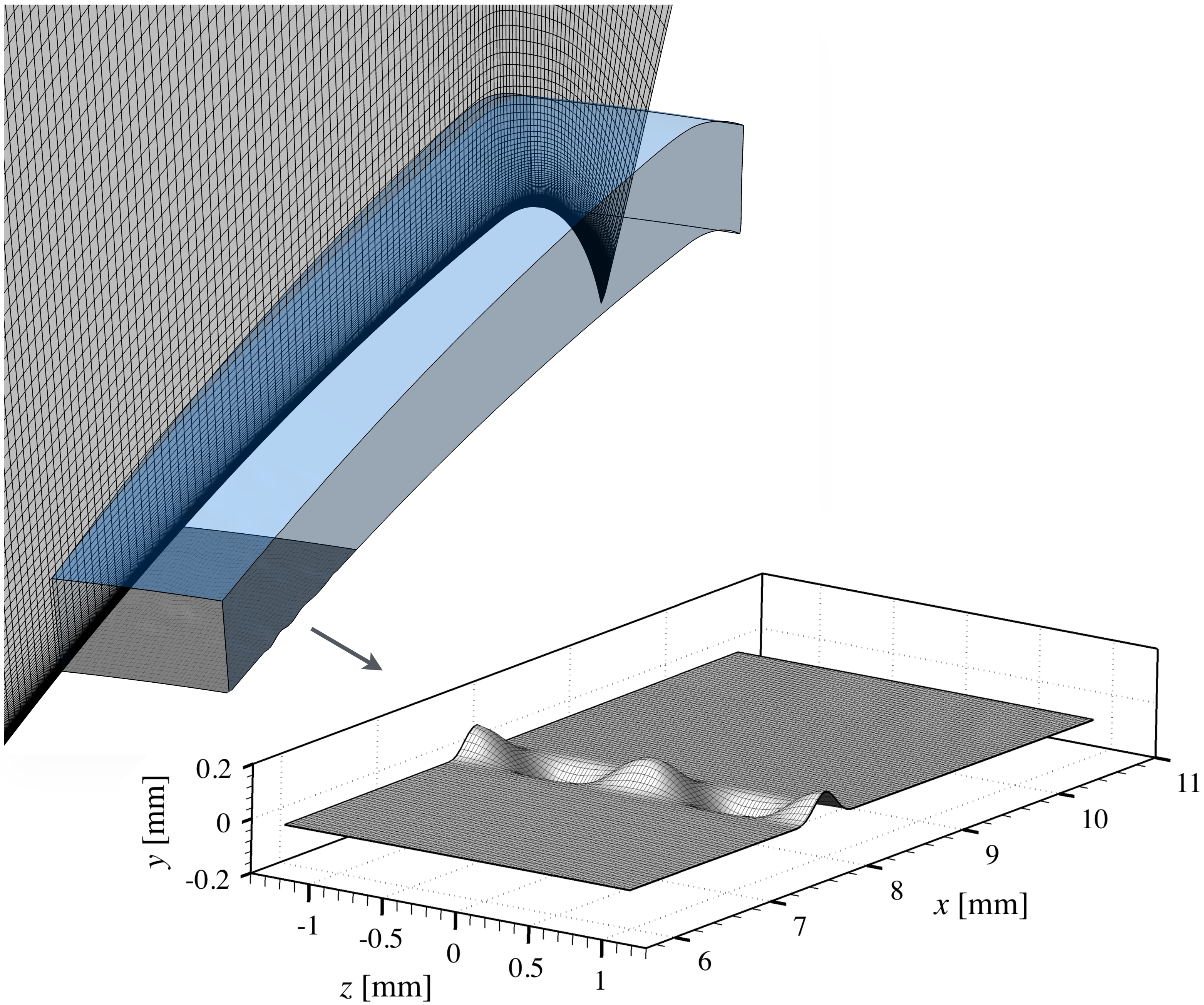
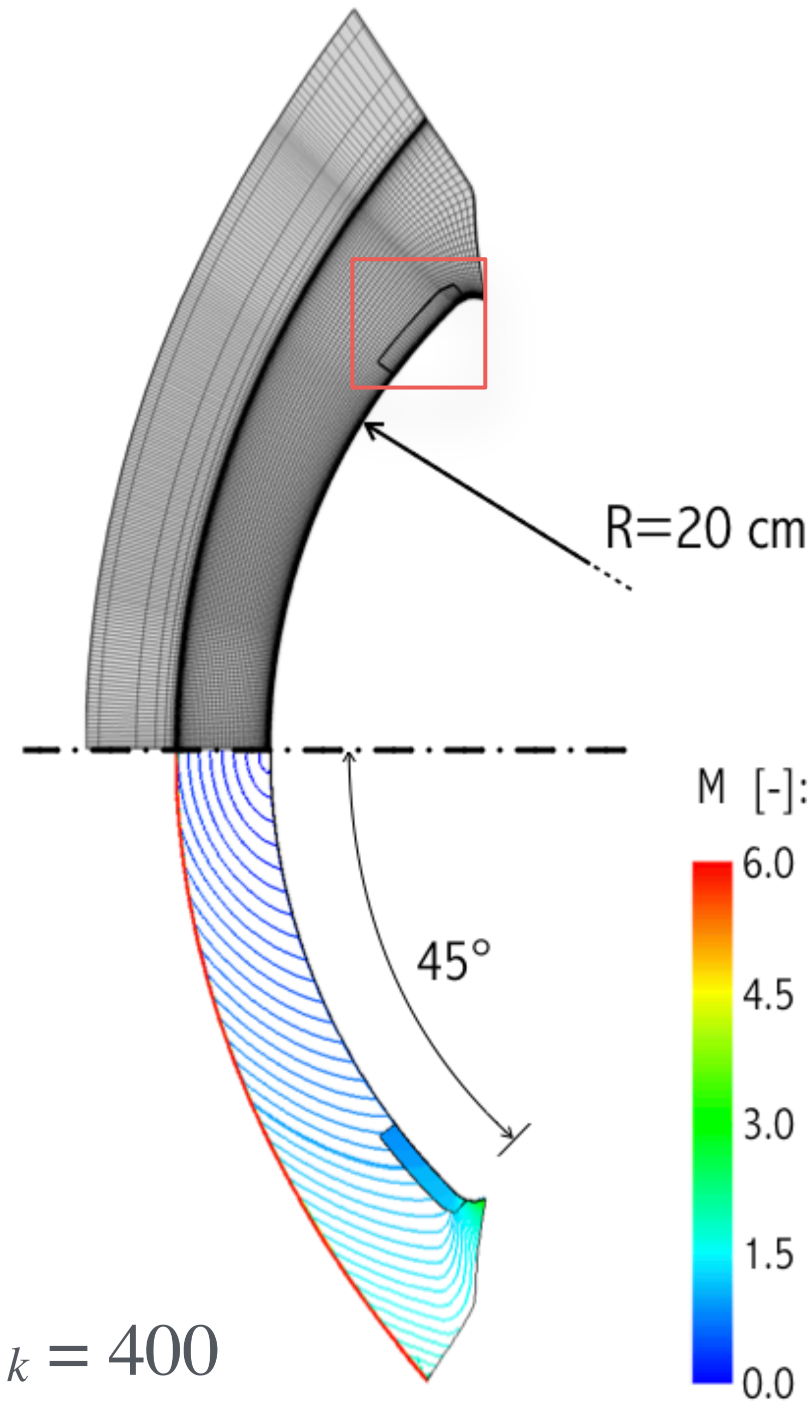
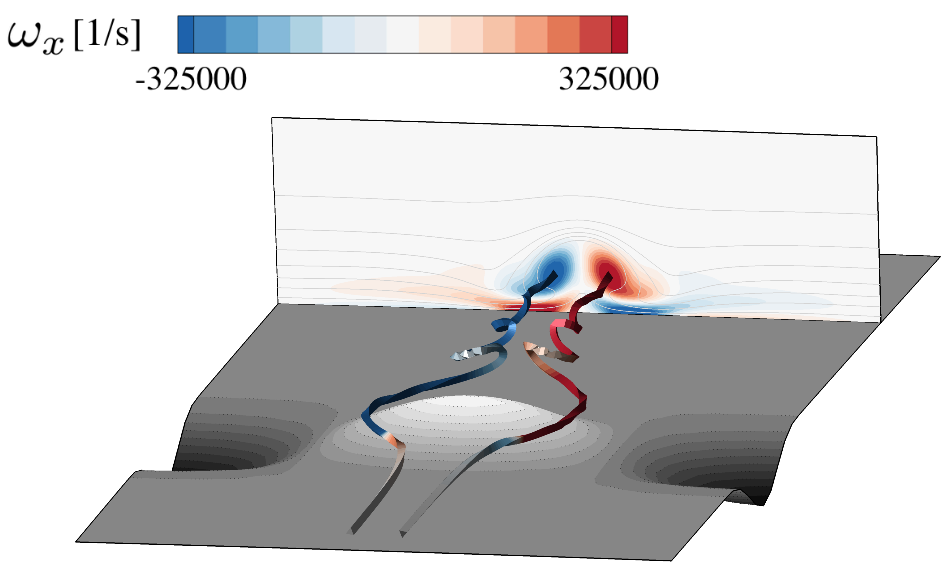




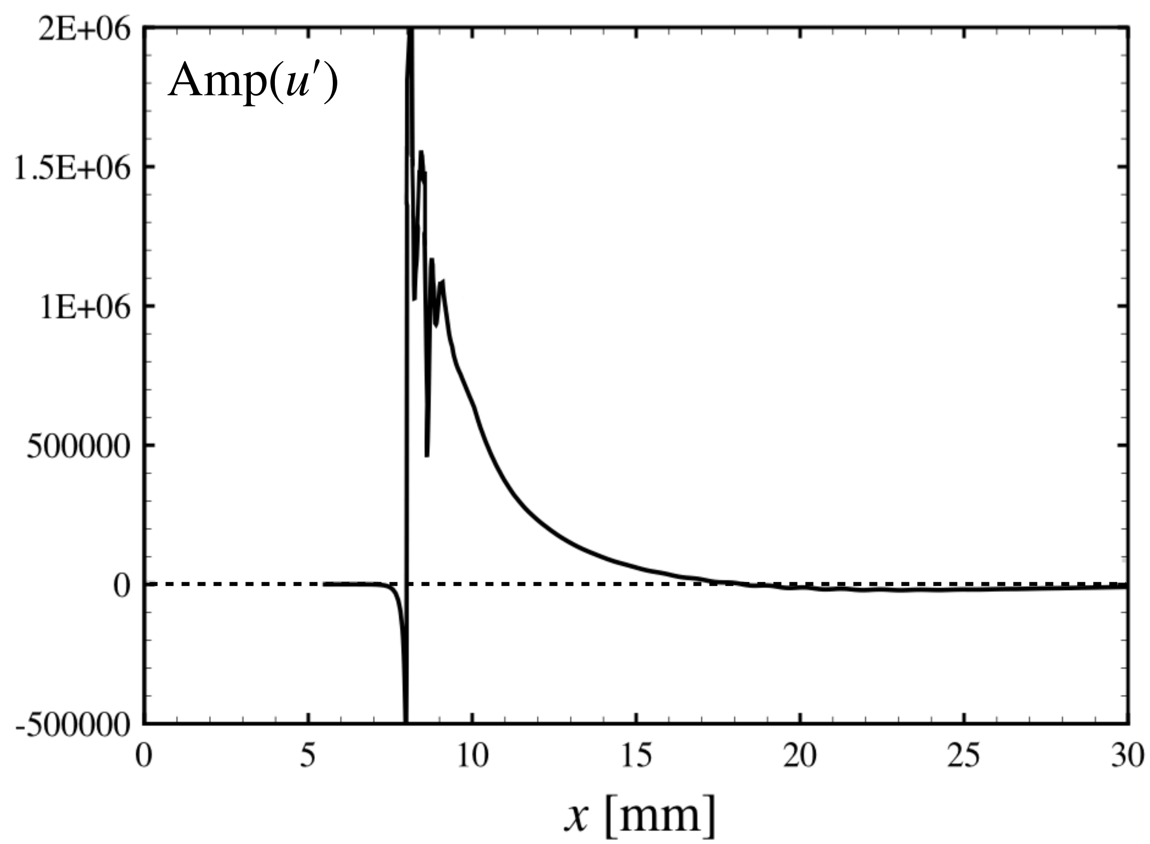
simple rgh: $k = 100\,\mu\text{m}$ $k/\delta = 0.35$ $Re_{kk} = u_k \varrho_k k/\mu_k = 400$

Analysis of a “simple” Roughness



- Counter-rotating vortices originate in the roughness wake
- Roughness wake decays rapidly

Amplitude of the roughness wake



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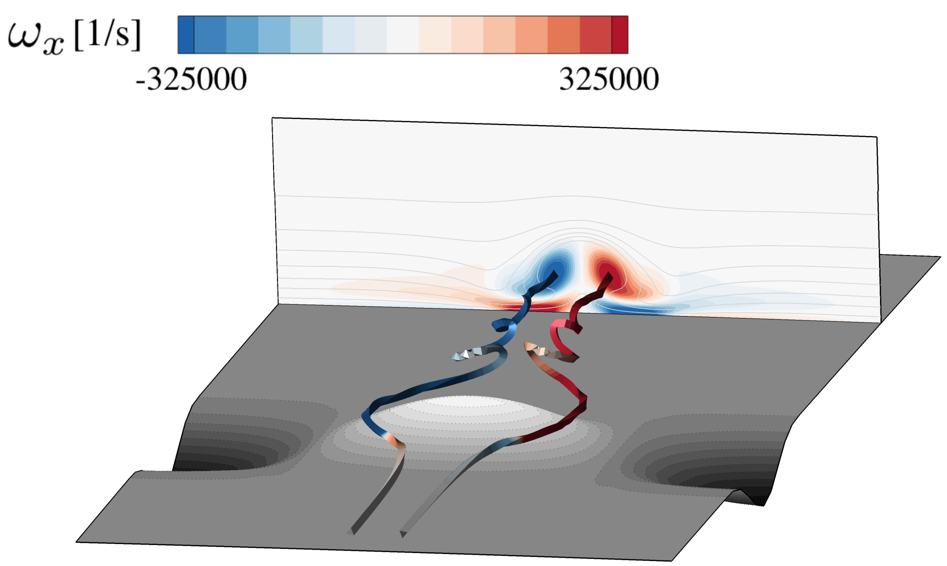

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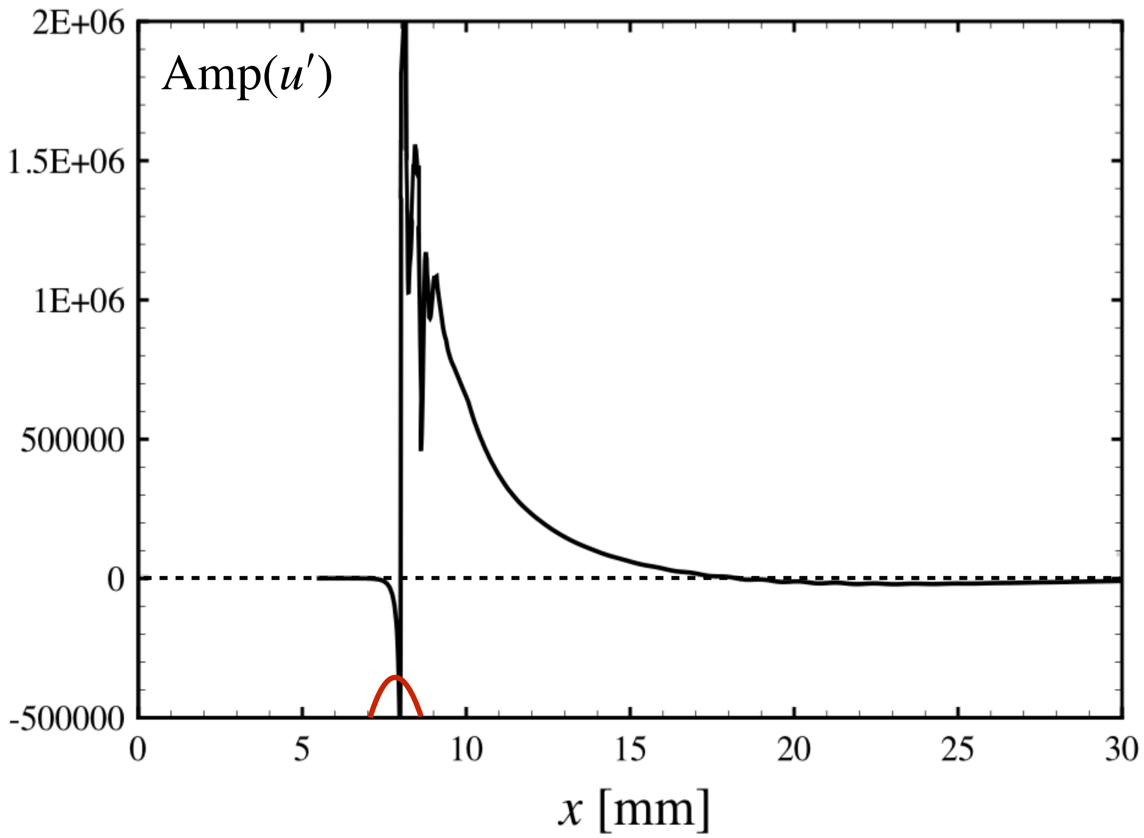
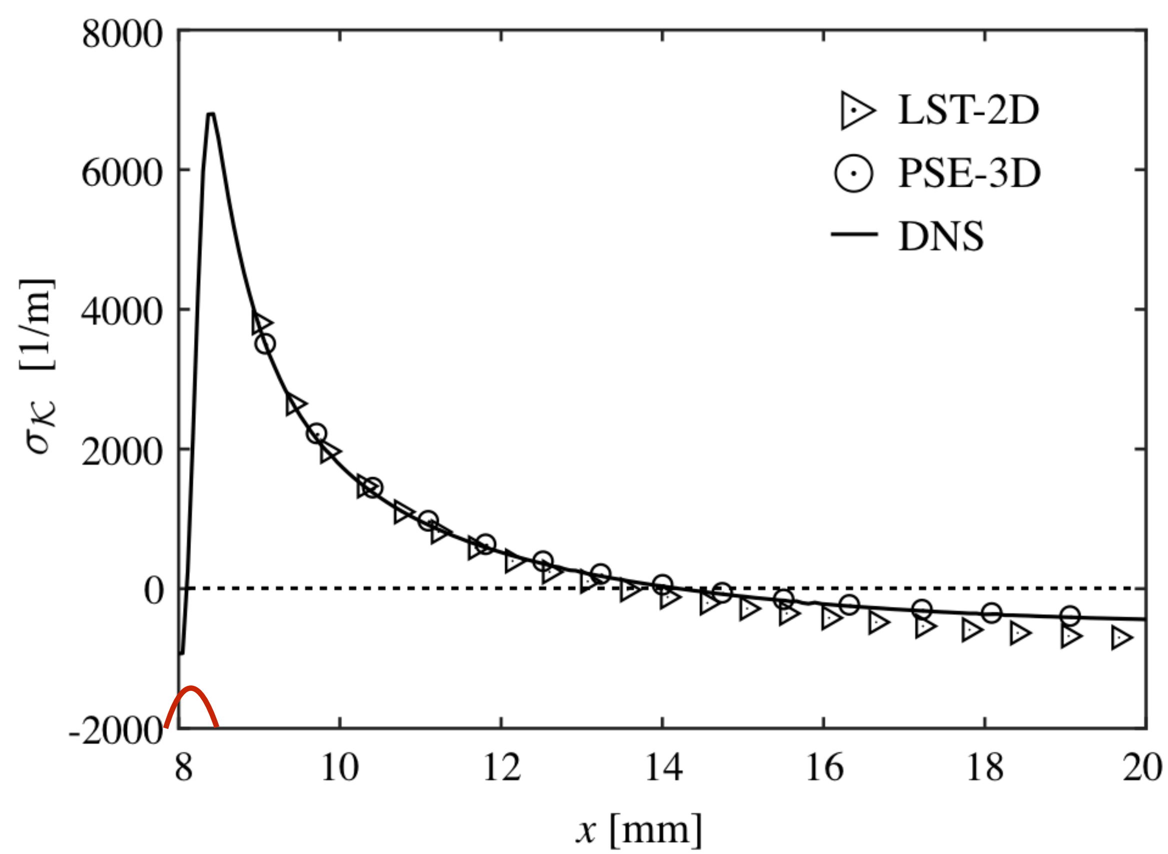
- Roughness wake decays rapidly

- N-factor = $\log(A_{max}/A_{in})$ ~ 8 (included roughness)

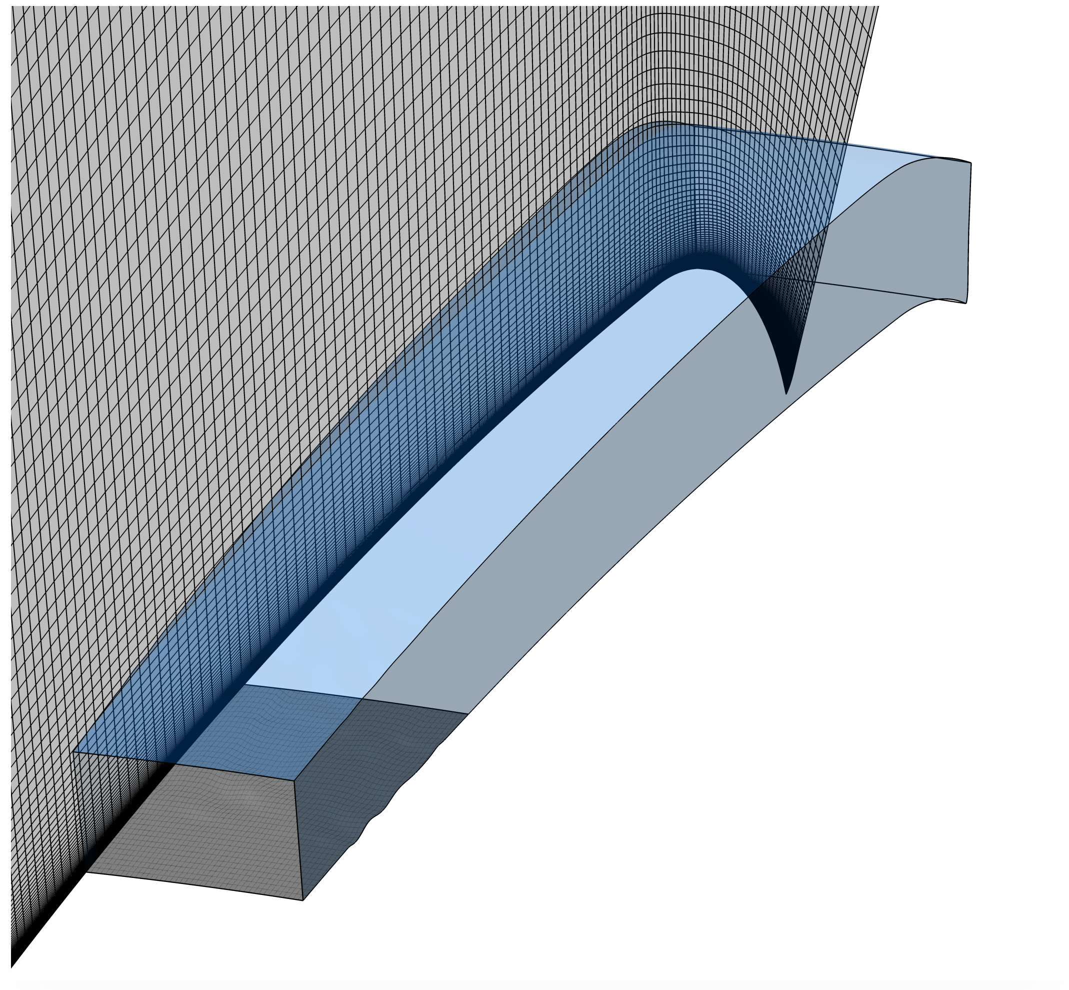
Amplitude of the roughness wake

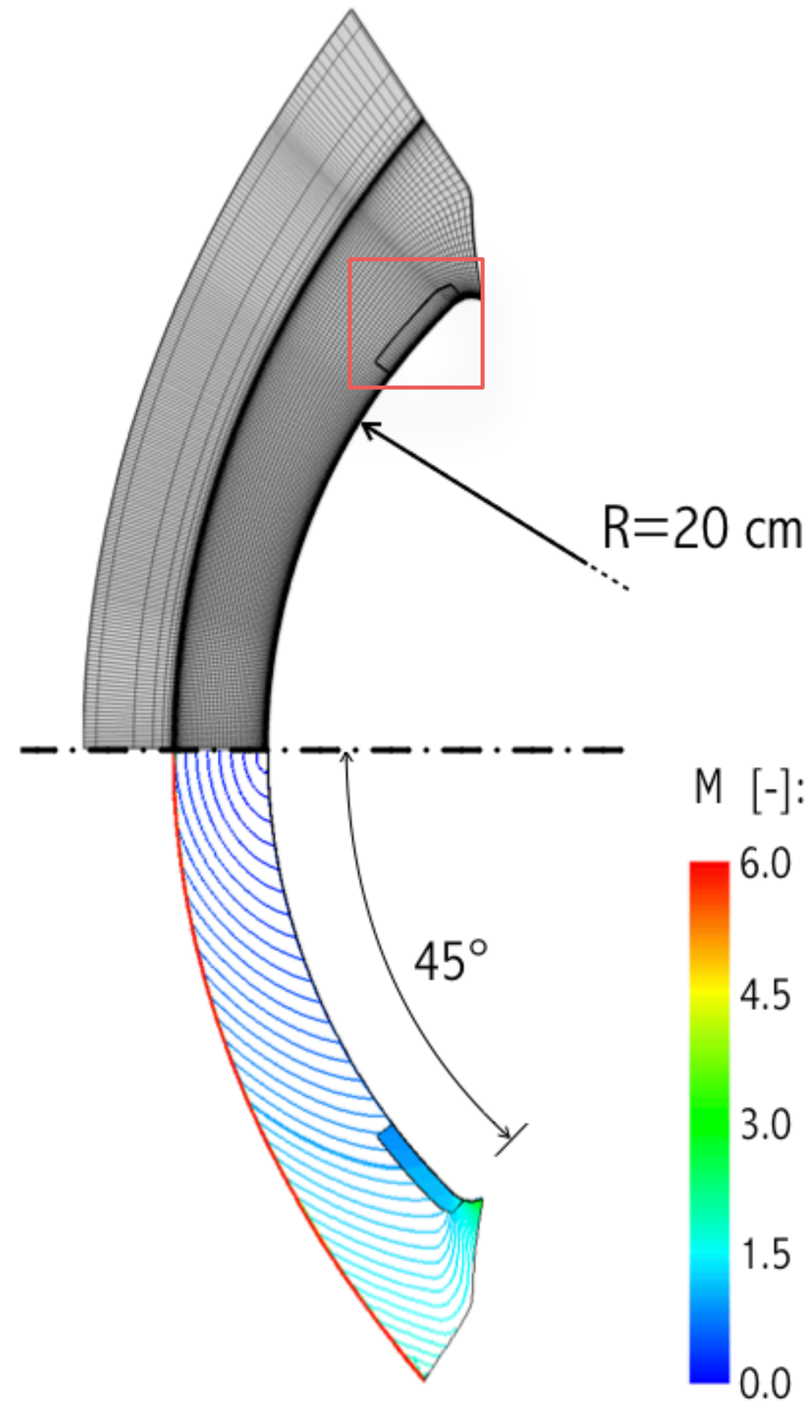


Growth rate (disturbance at 250 kHz)



Definition of a *distributed* Roughness





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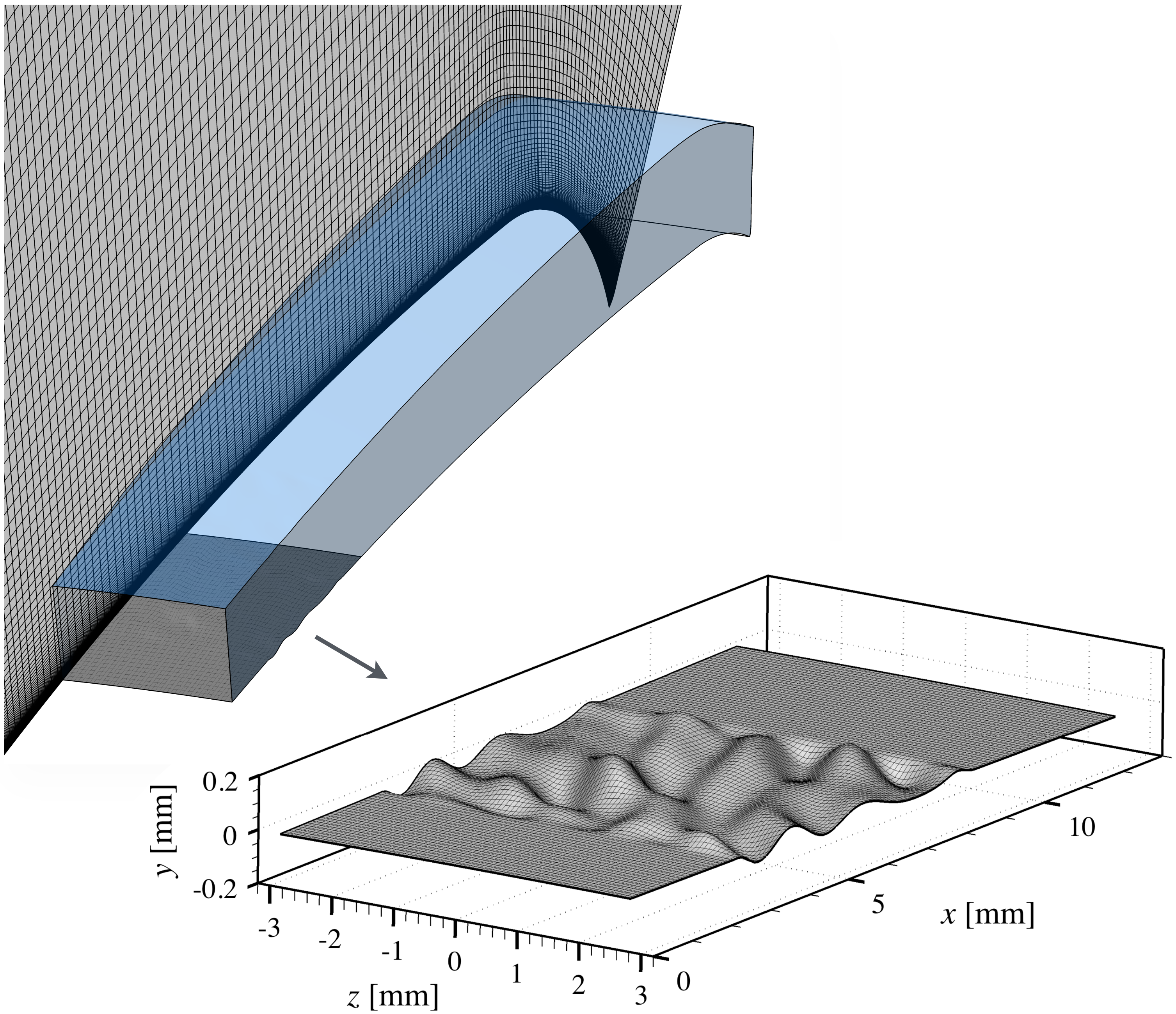

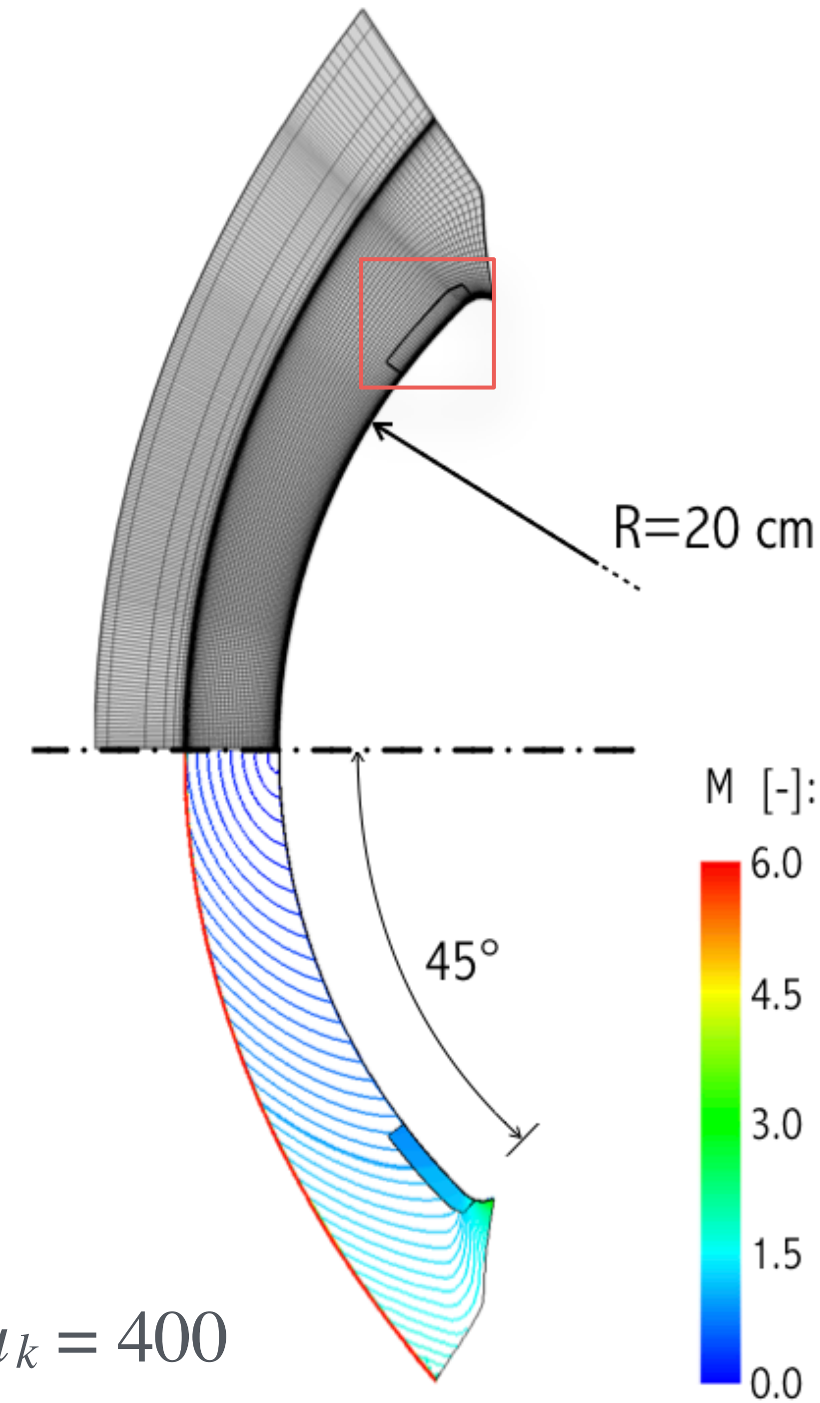

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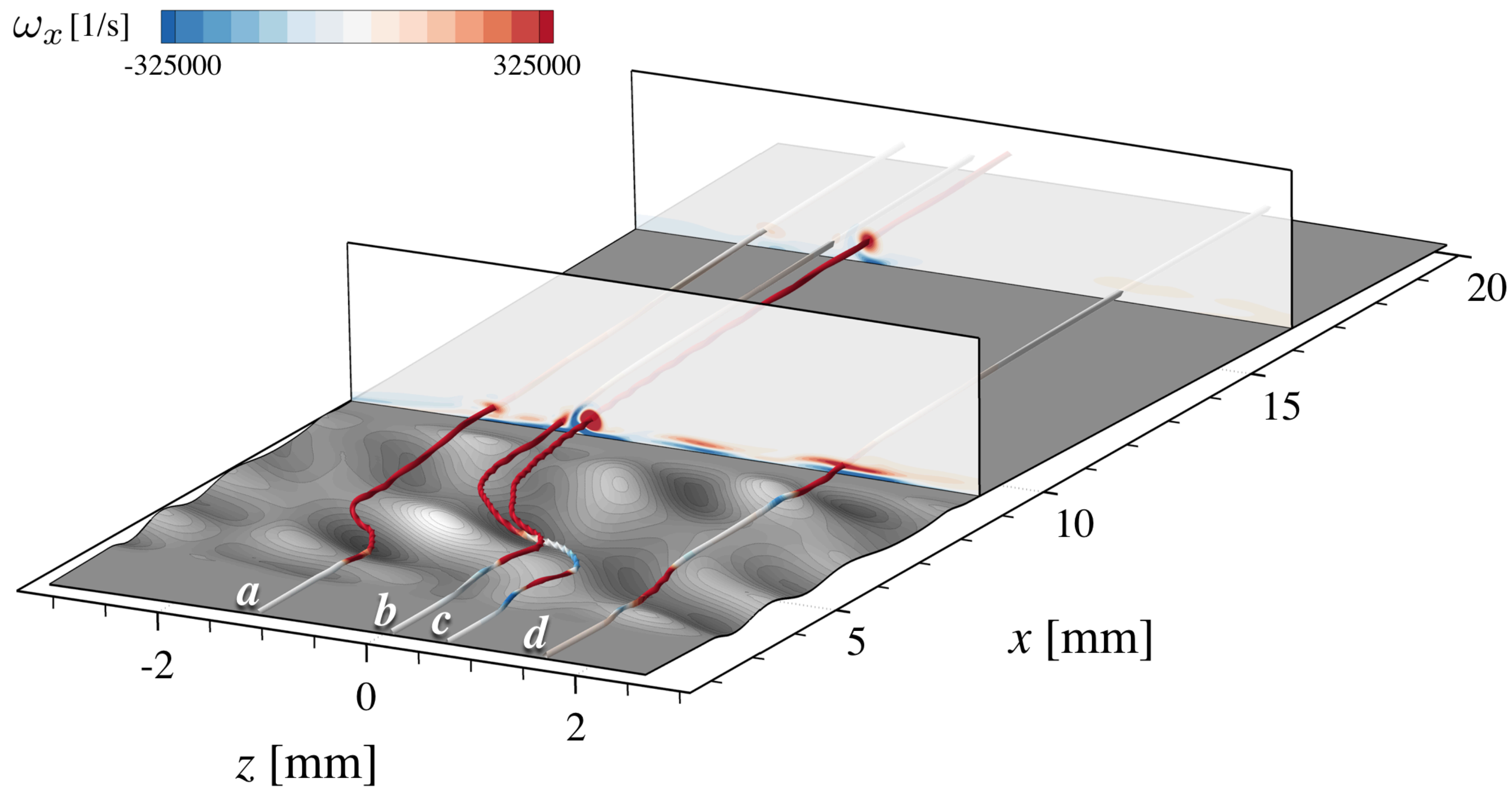
Steady Base Flow

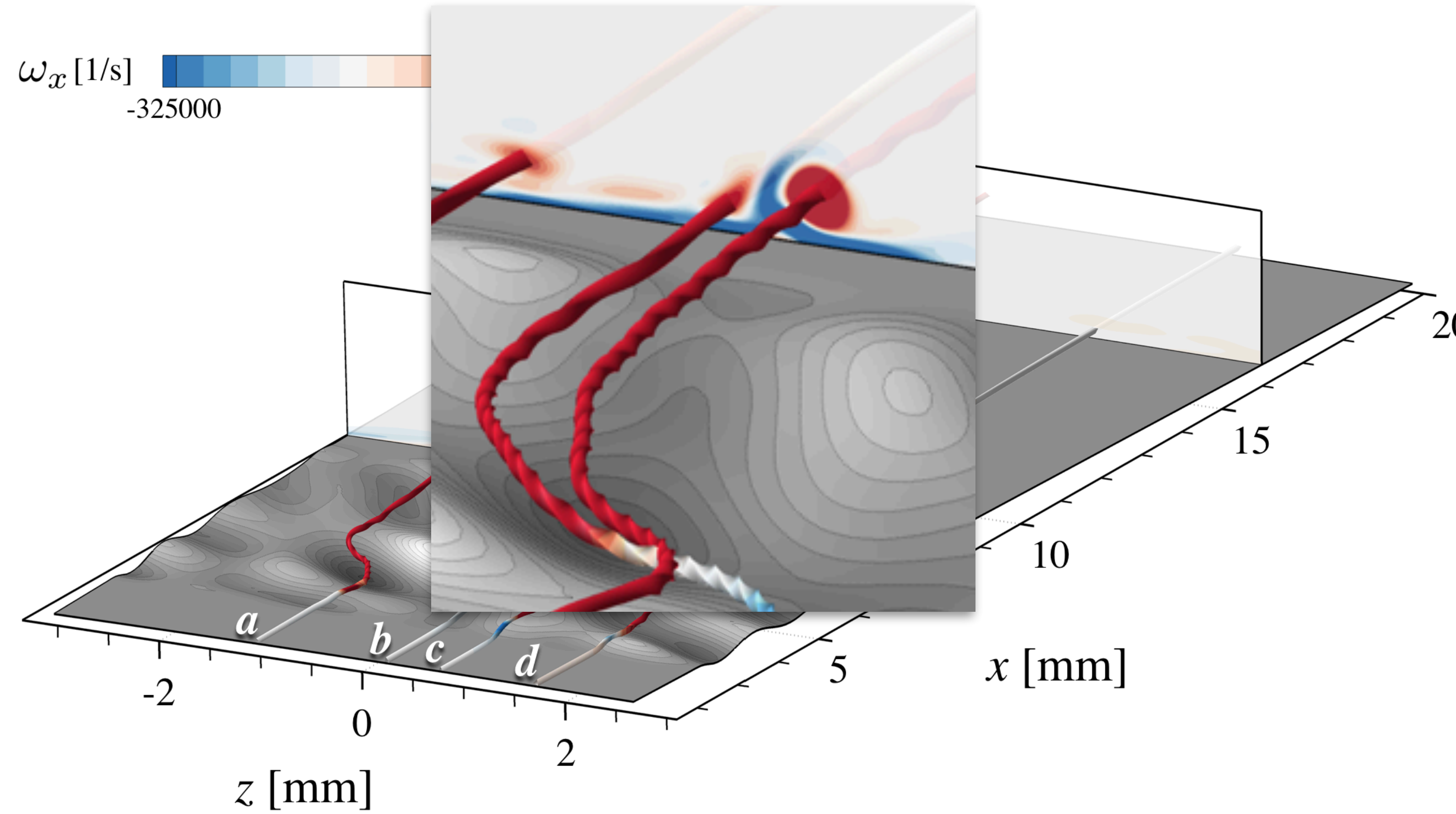
- Multiple vorticity regions in the roughness wake

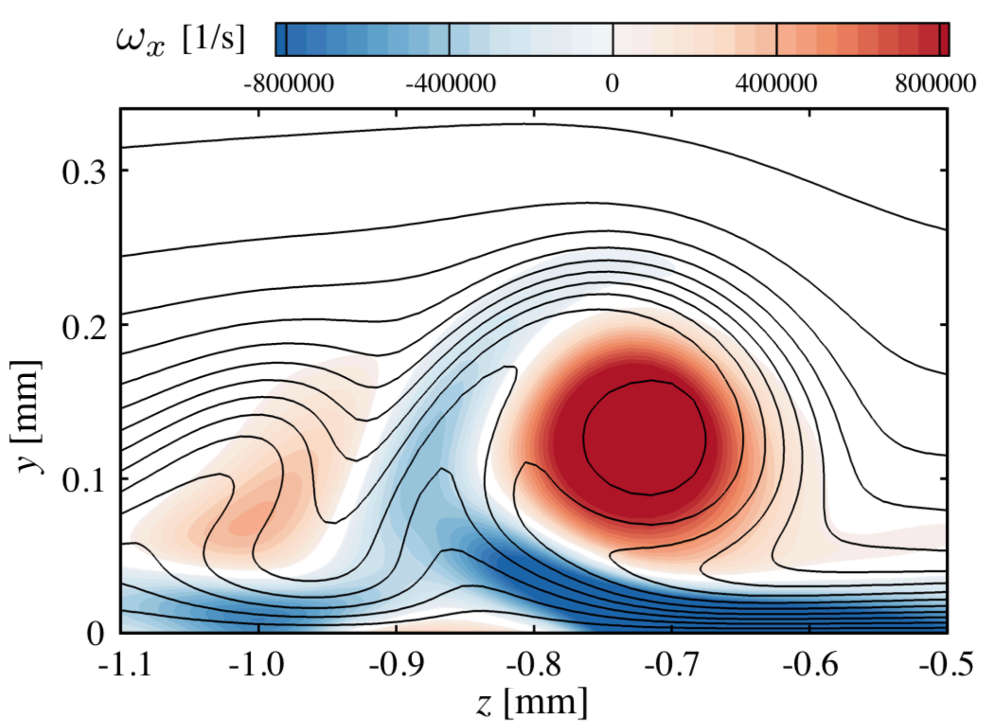


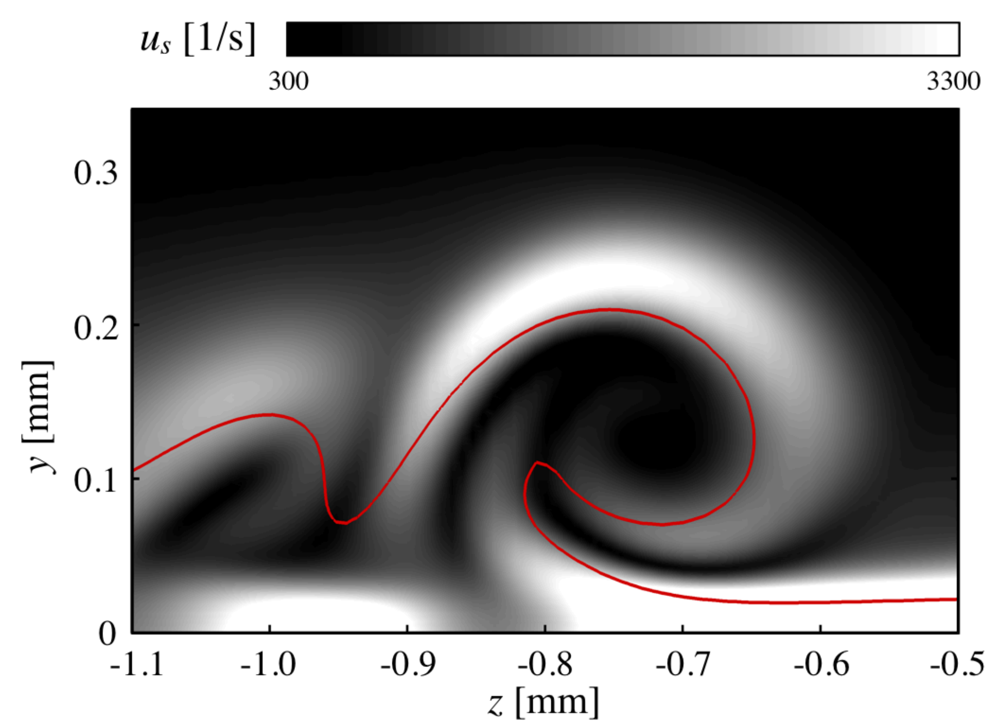
Steady Base Flow: Crossflow-type Vortex

Multiple vorticity regions in the roughness wake

- Formation of a crossflow-type vortex due to the spanwise velocity induced by the skewness of the roughness





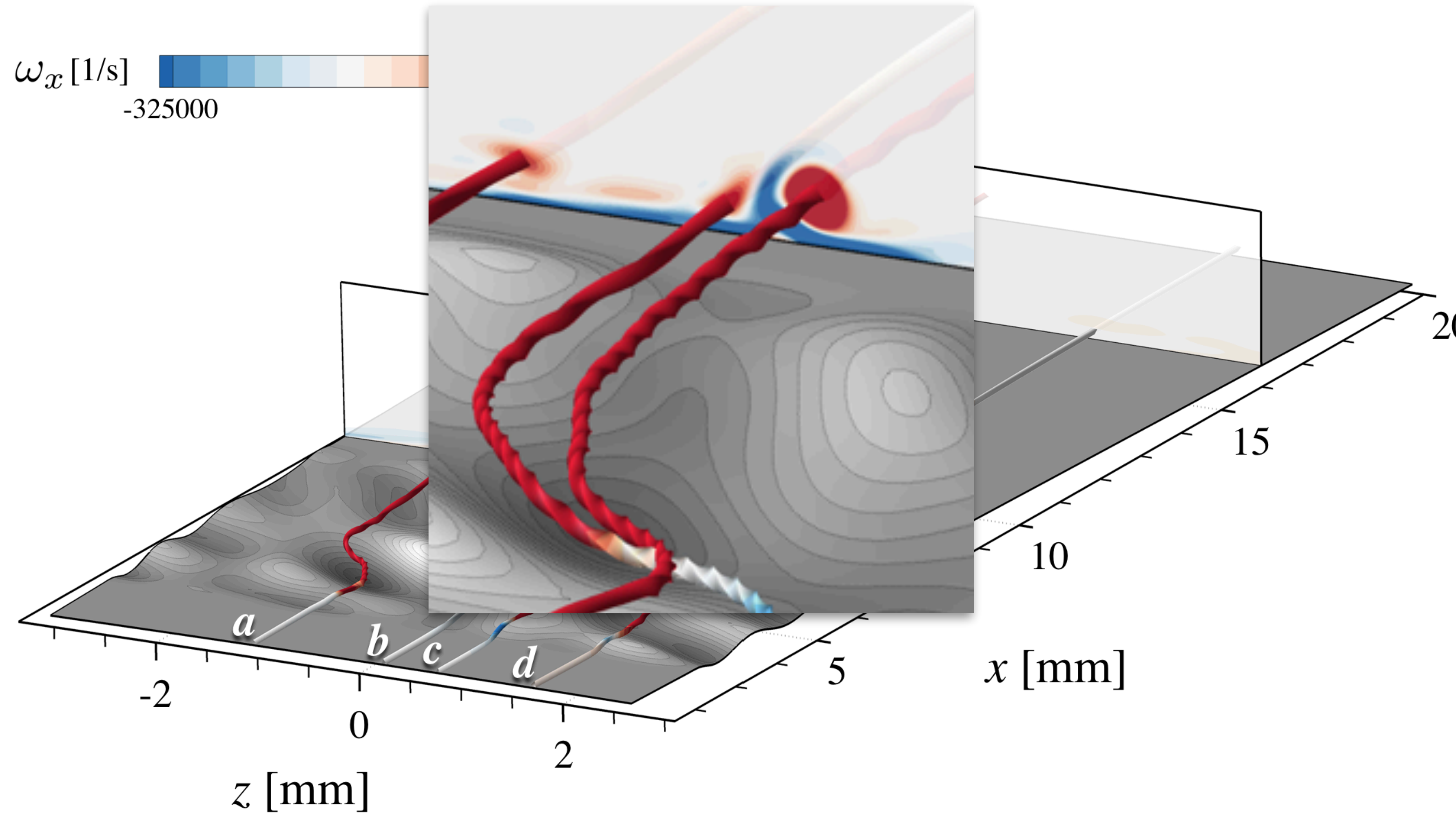


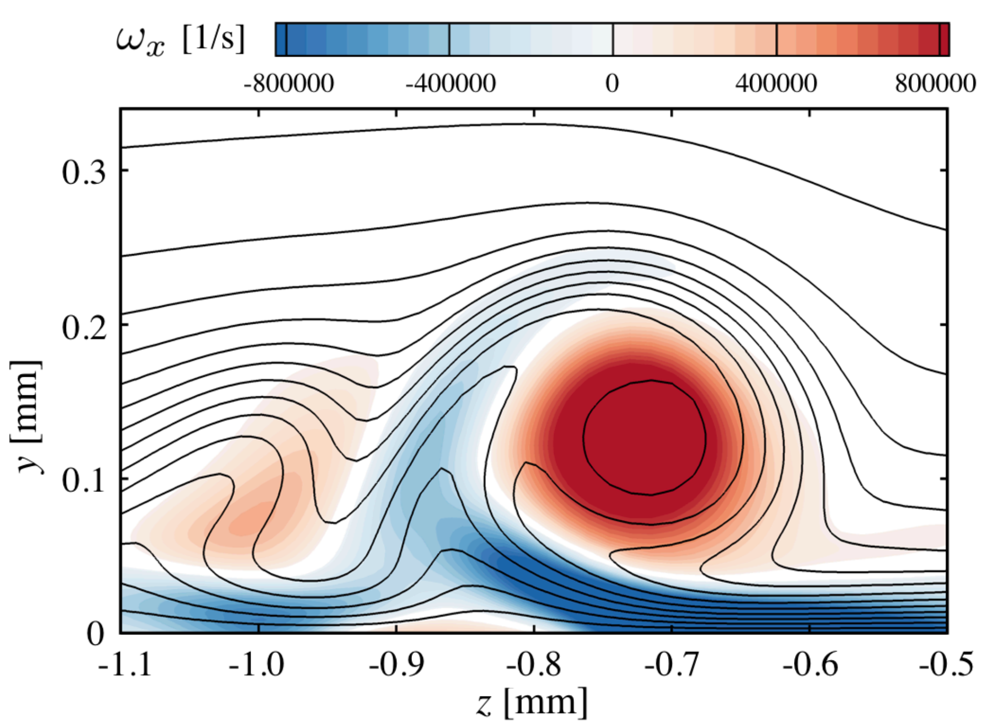
Steady Base Flow: Crossflow-type Vortex

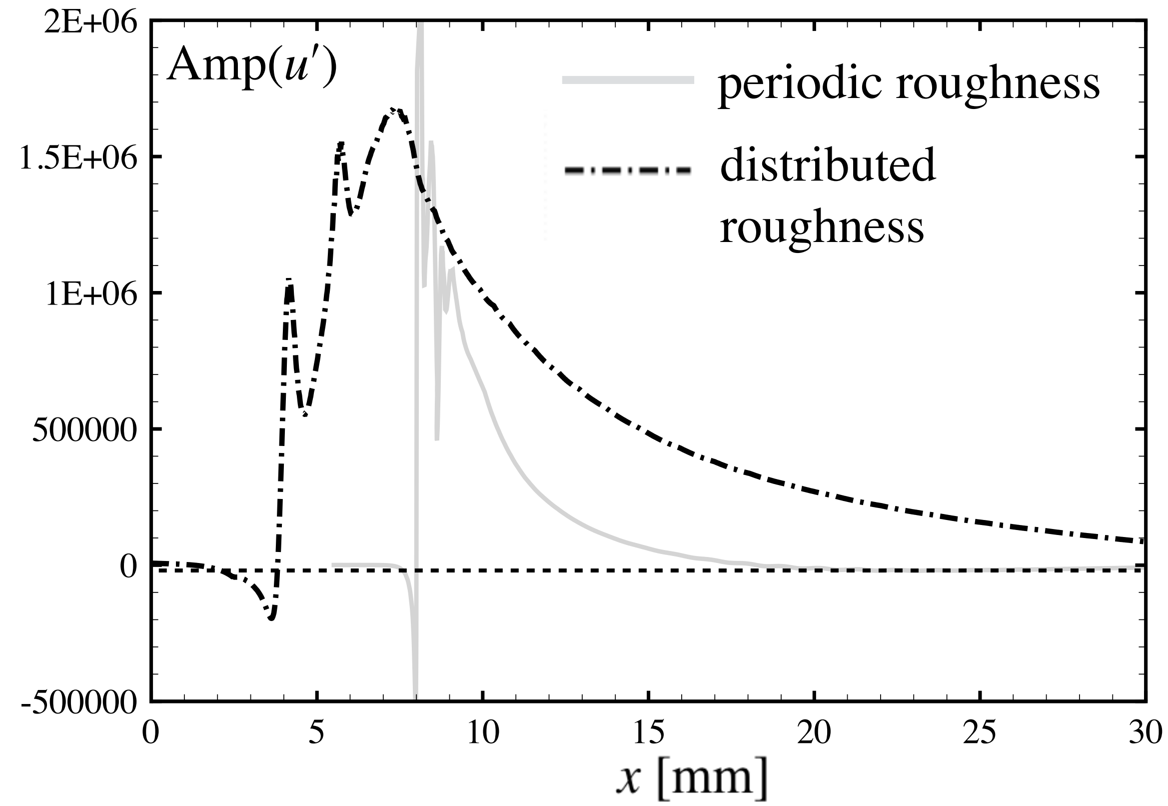
Multiple vorticity regions in the roughness wake

Formation of a crossflow-type vortex due to the spanwise velocity induced by the skewness of the roughness

- The crossflow-type vortex is very persistent in the accelerated boundary layer



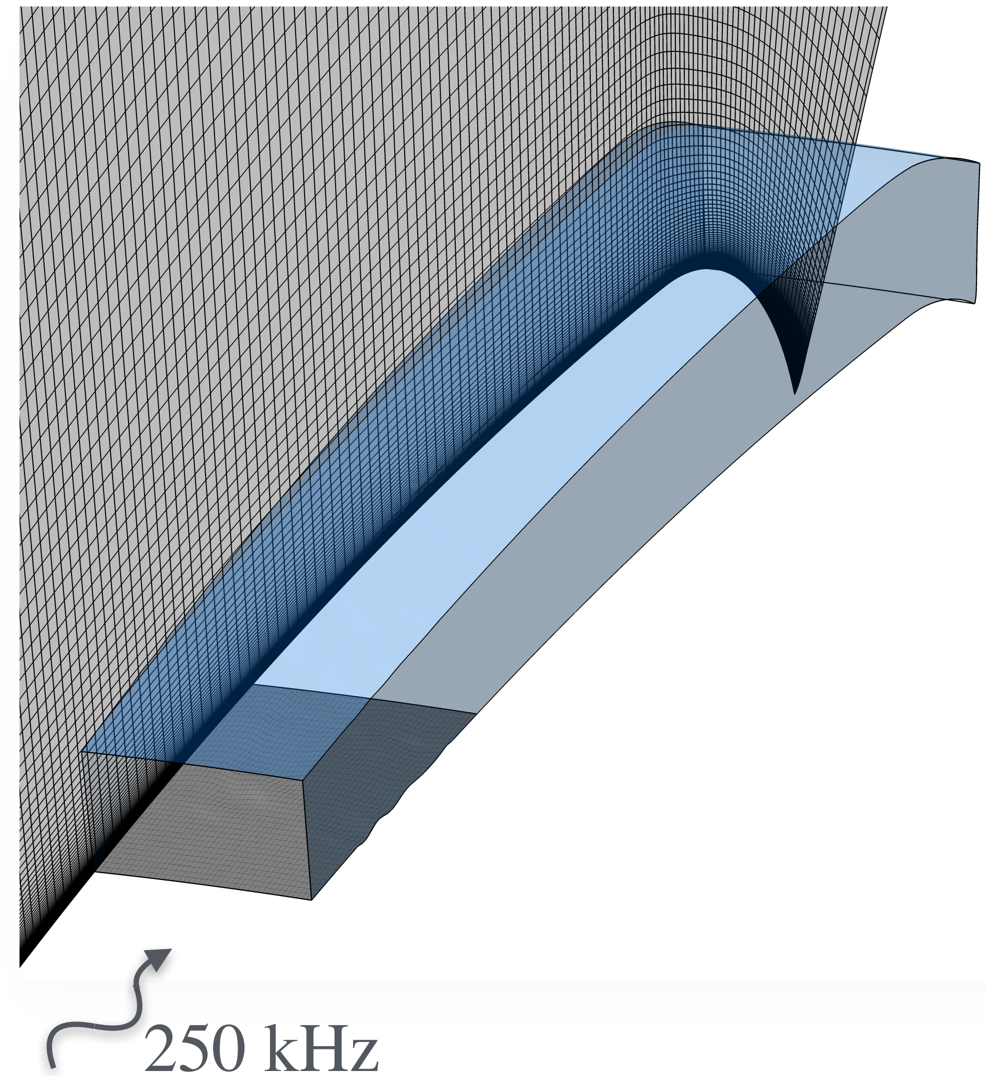




DNS-based Stability Analysis

We force at the inflow

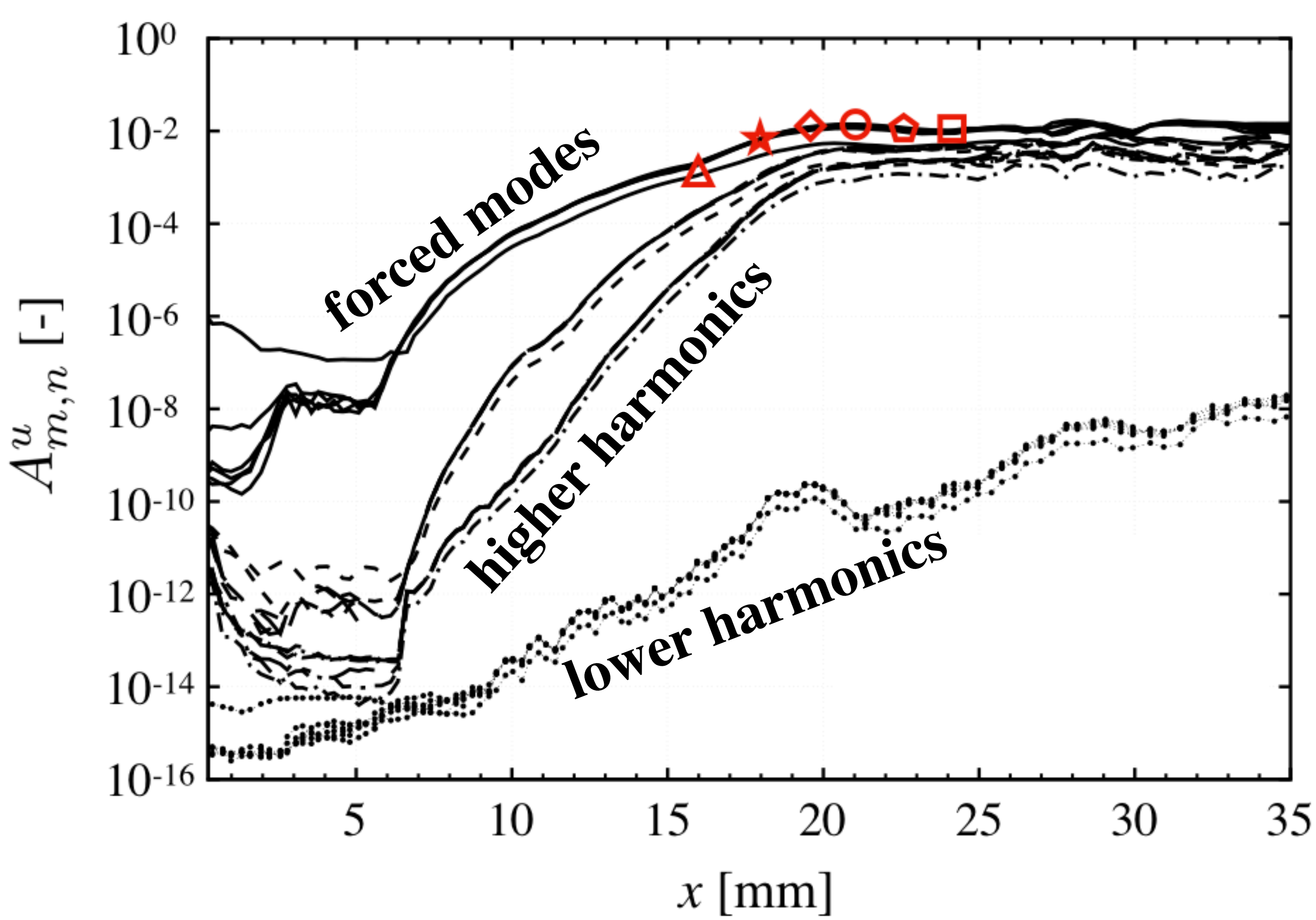
- small acoustic disturbances
- upstream of the roughness patch
- at 250 kHz (forced mode)



Analysis is carried out through

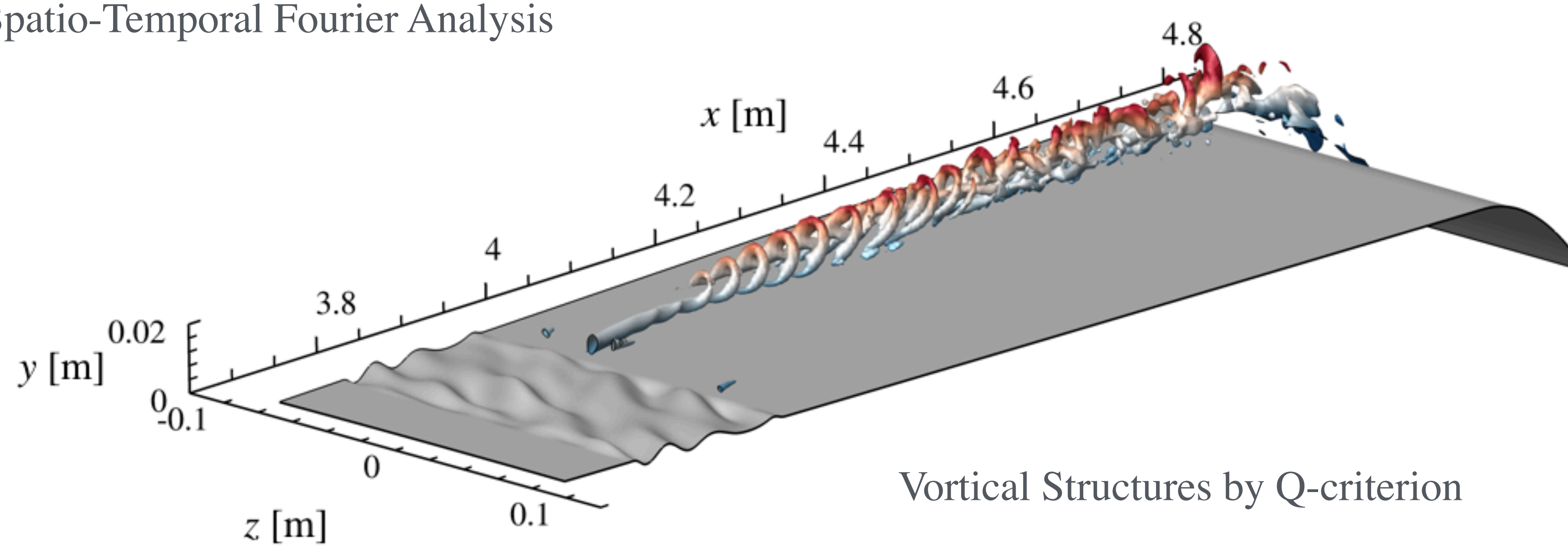
- spatio-temporal Fourier transform
  (spanwise wavenumber - frequency)

DNS-based Stability Analysis



Results of the Spatio-Temporal Fourier Analysis

- harmonics of the forced frequency non-linearly driven in the roughness wake
- observed N-factor > 13 (cf. N=8 for single roughness, k and Re_{kk} being equal)
- small interaction with the roughness (forced modes remain dominant up to growth saturation)



Vortical Structures by Q-criterion

Investigations under Windtunnel Conditions: most relevant results[2] so far…

a. The skewness of protuberances as obtained in the presence of (pseudo-)random distributed roughness induces a spanwise component of the velocity which is not present in the original two-dimensional base flow. A crossflow-type vortex is generated.

b. The crossflow-type vortex is significantly more persistent than the pair of counter-rotating vortices originated at symmetrical roughness elements, at same height and Re_{kk}.

c. Accordingly, a stronger amplification of forced disturbances is found — A new type of roughness-induced crossflow-type transition mechanism was observed for the blunt-body configuration.

d. Comparison with experiments: difficult (no experiments available for only a "patch" of distributed roughness), but there is an ongoing cooperation with TU Braunschweig, Germany.

[2] Di Giovanni & Stemmer: "Crossflow-type breakdown induced by distributed roughness in the boundary layer of a hypersonic capsule configuration ", *J. Fluid Mechanics*, 2018 (accepted)

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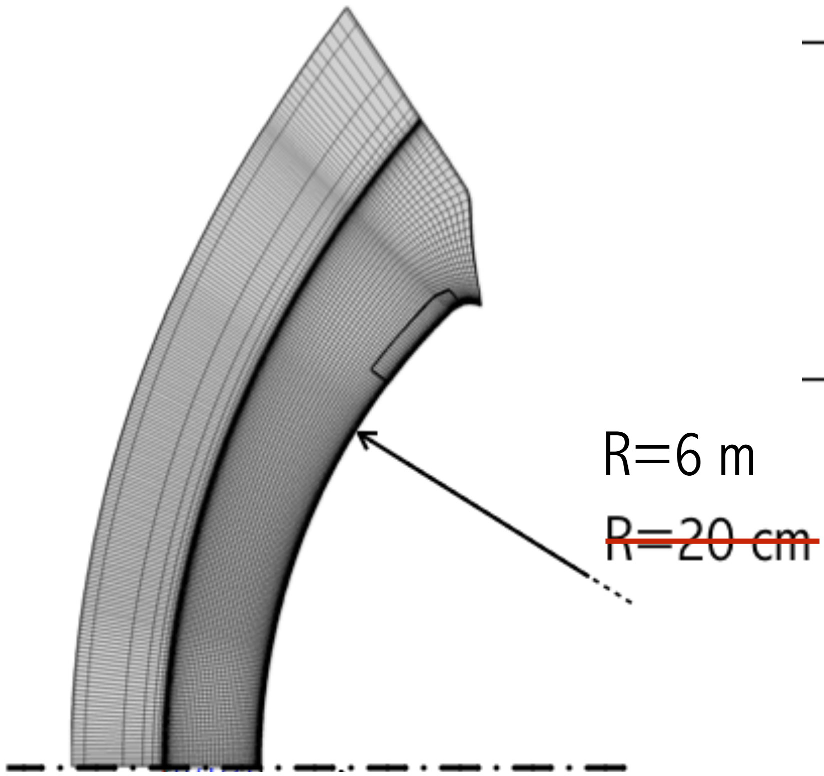
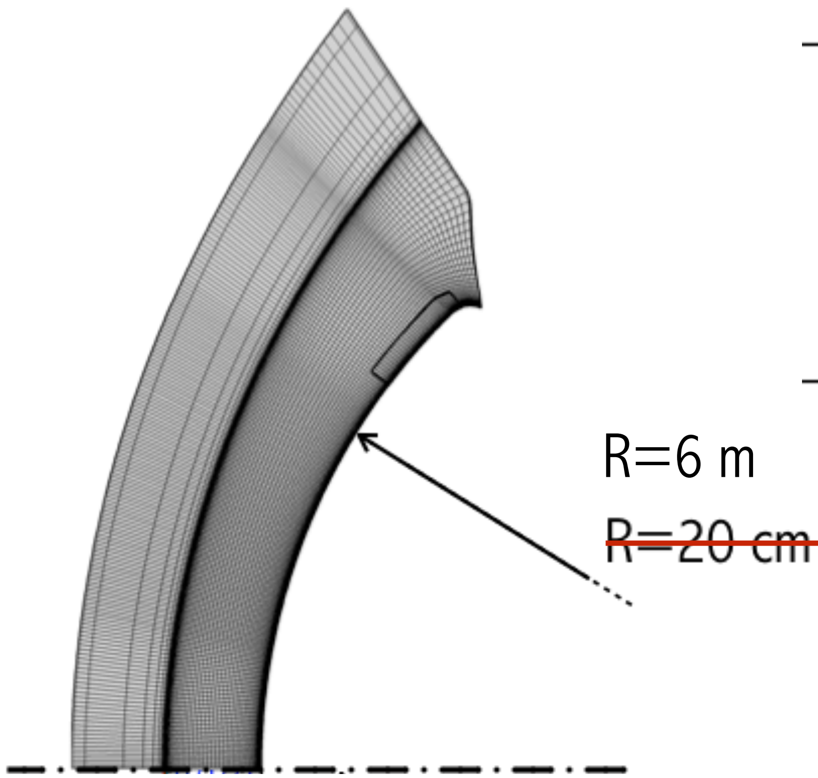


Medium	M	T_∞ [K]	T_w [K]	Re_∞ [1/m]	R [m]
Air	20	253	1800	$2 \cdot 10^6$	6

TABLE 2. Simulation parameters - re-entry conditions

Simulations at Re-entry Conditions



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Different simulations are run with 3 different gas models:

1. gas in chemical equilibrium (CEQ)
   ($T > 2000$ K)

$$N_2 \quad O_2 \quad \rightleftharpoons \quad N \quad N_2 \quad O_2 \quad O \quad NO$$

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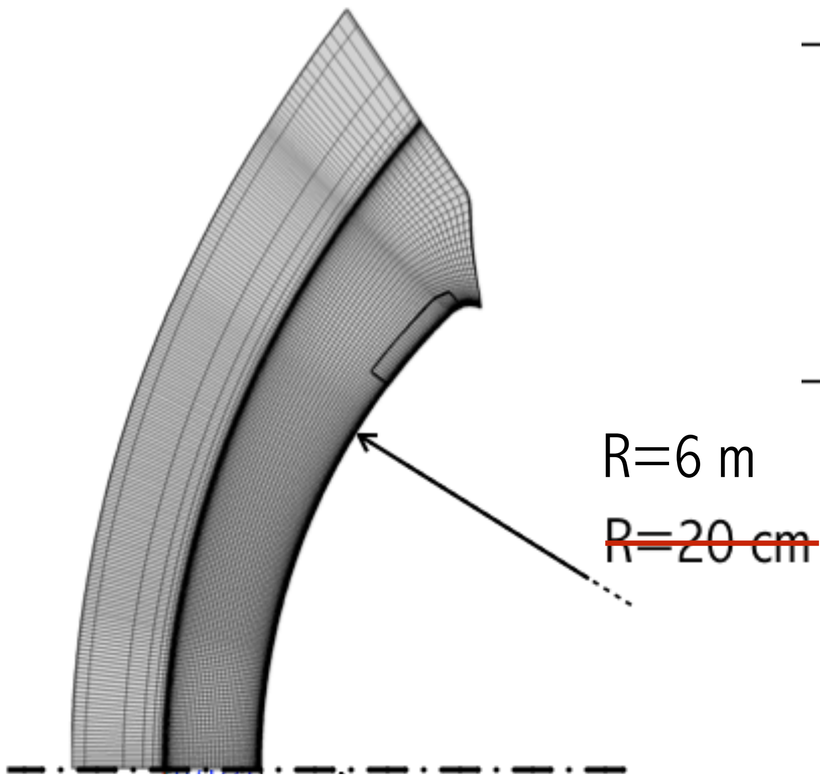

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2. gas in chemical NON-equilibrium (CNEQ)
   (timescale of reactions > timescale of convection)

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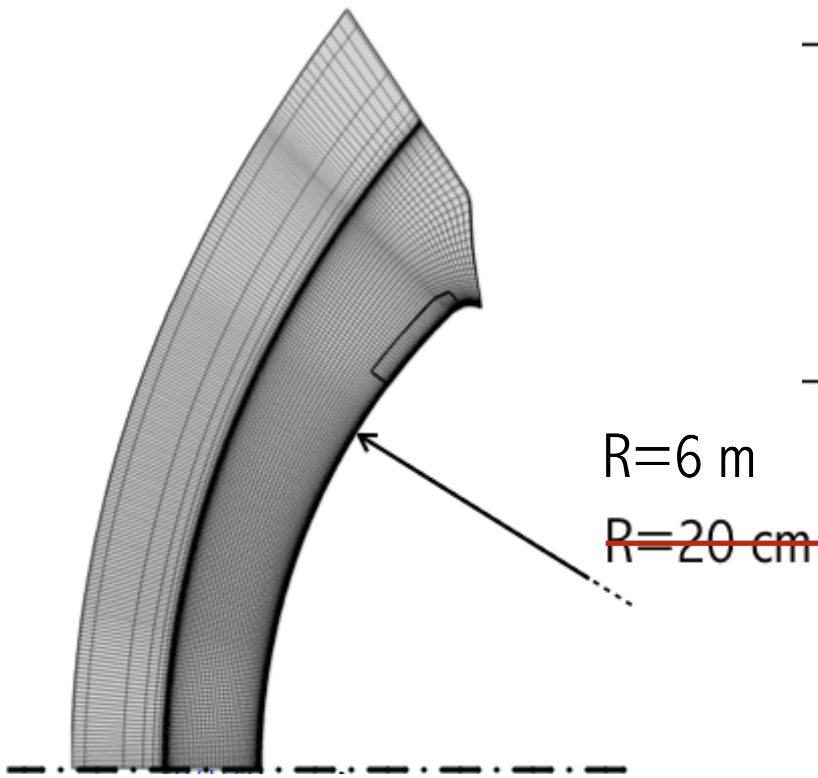

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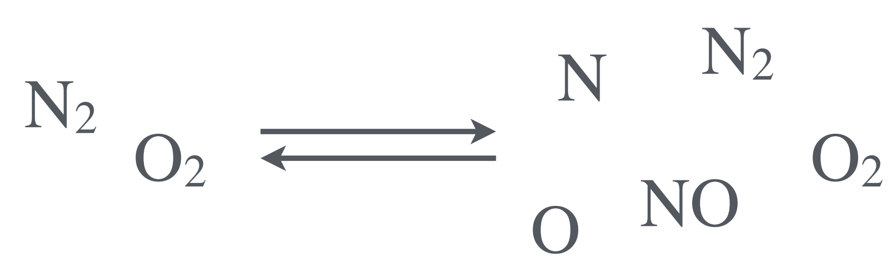
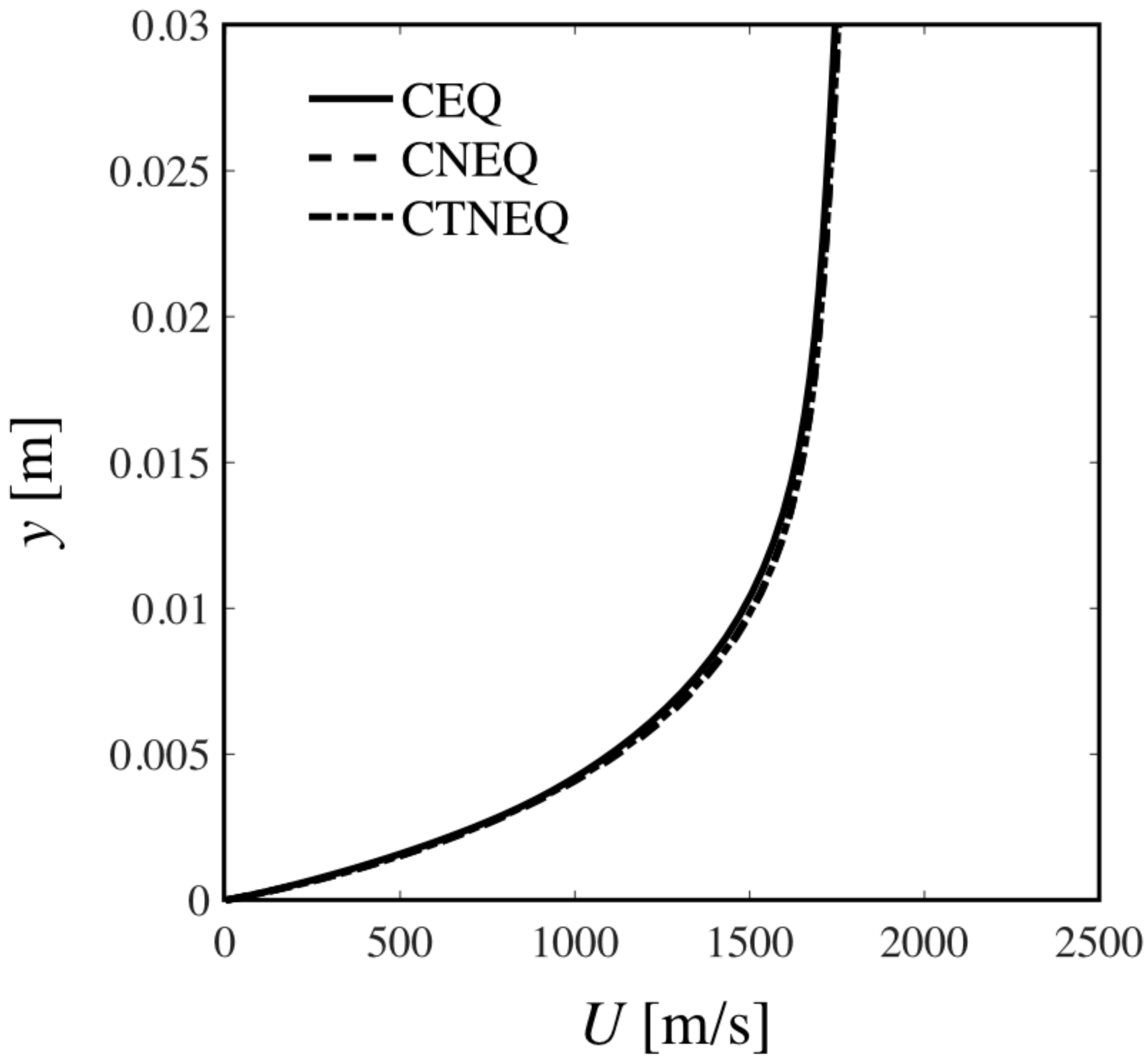
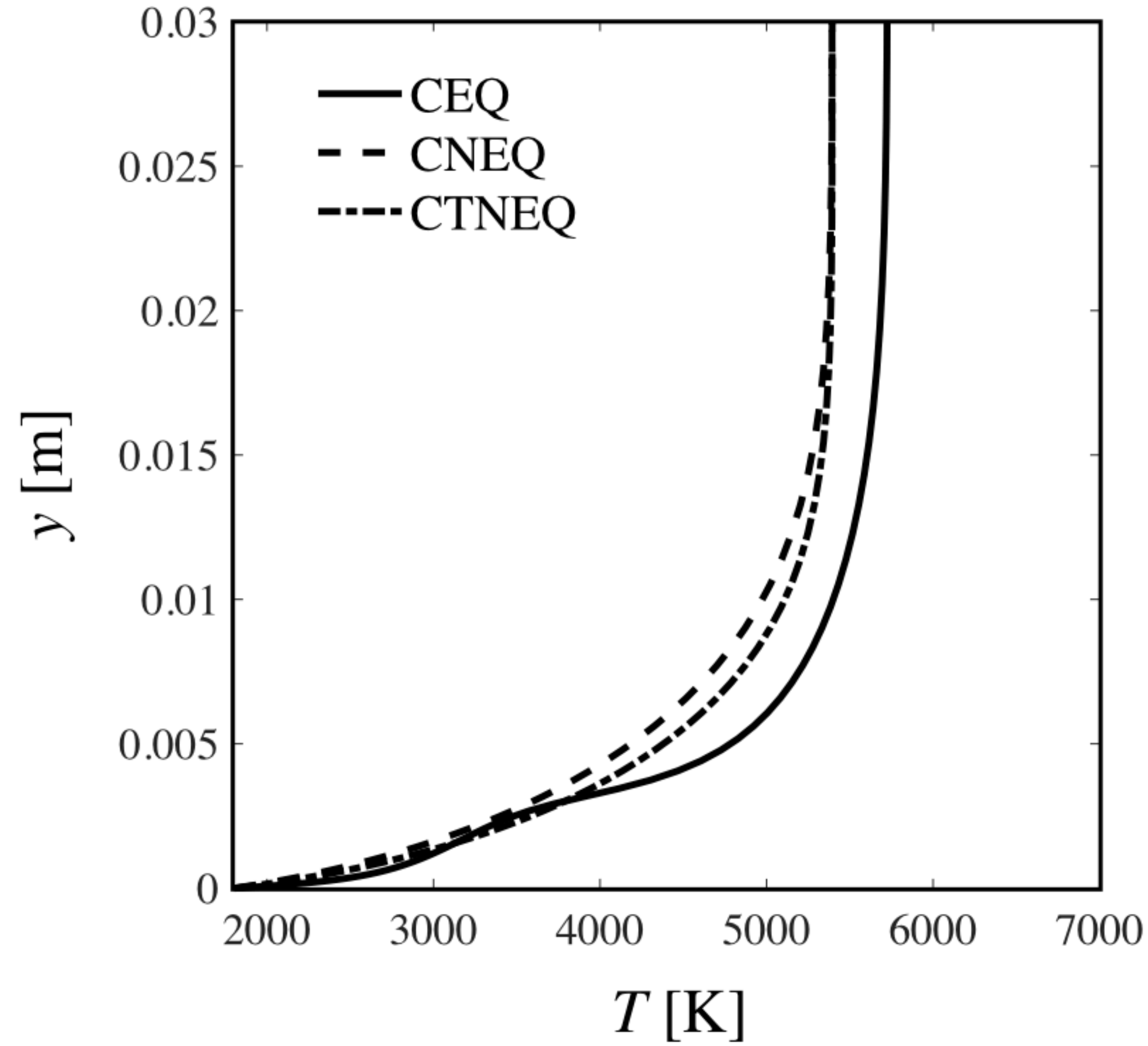


2. gas in chemical NON-equilibrium (CNEQ)
   (timescale of reactions > timescale of convection)

3. gas in thermal & chemical NON-equilibrium (CTNEQ)
   (timescale of vibration-energy change > timescale of convection)

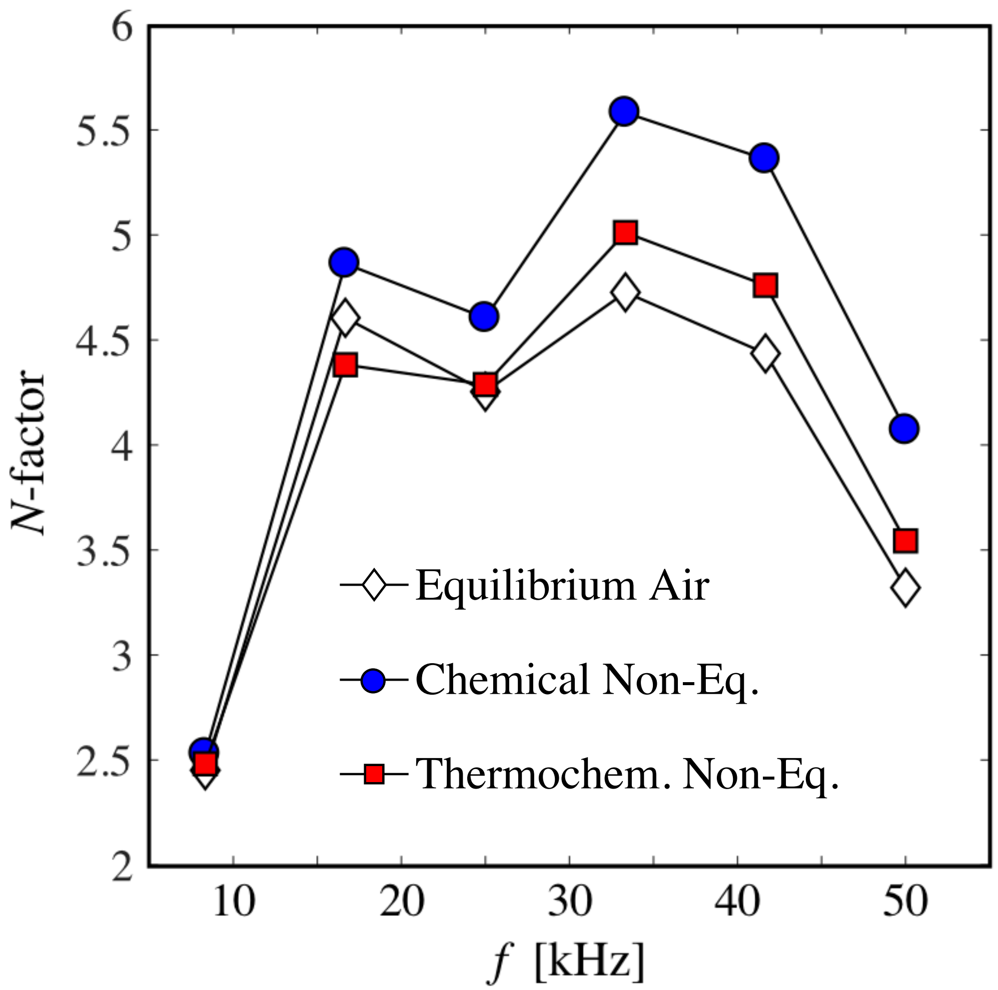
Effect of the Gas Modeling on the Boundary-Layer Profiles

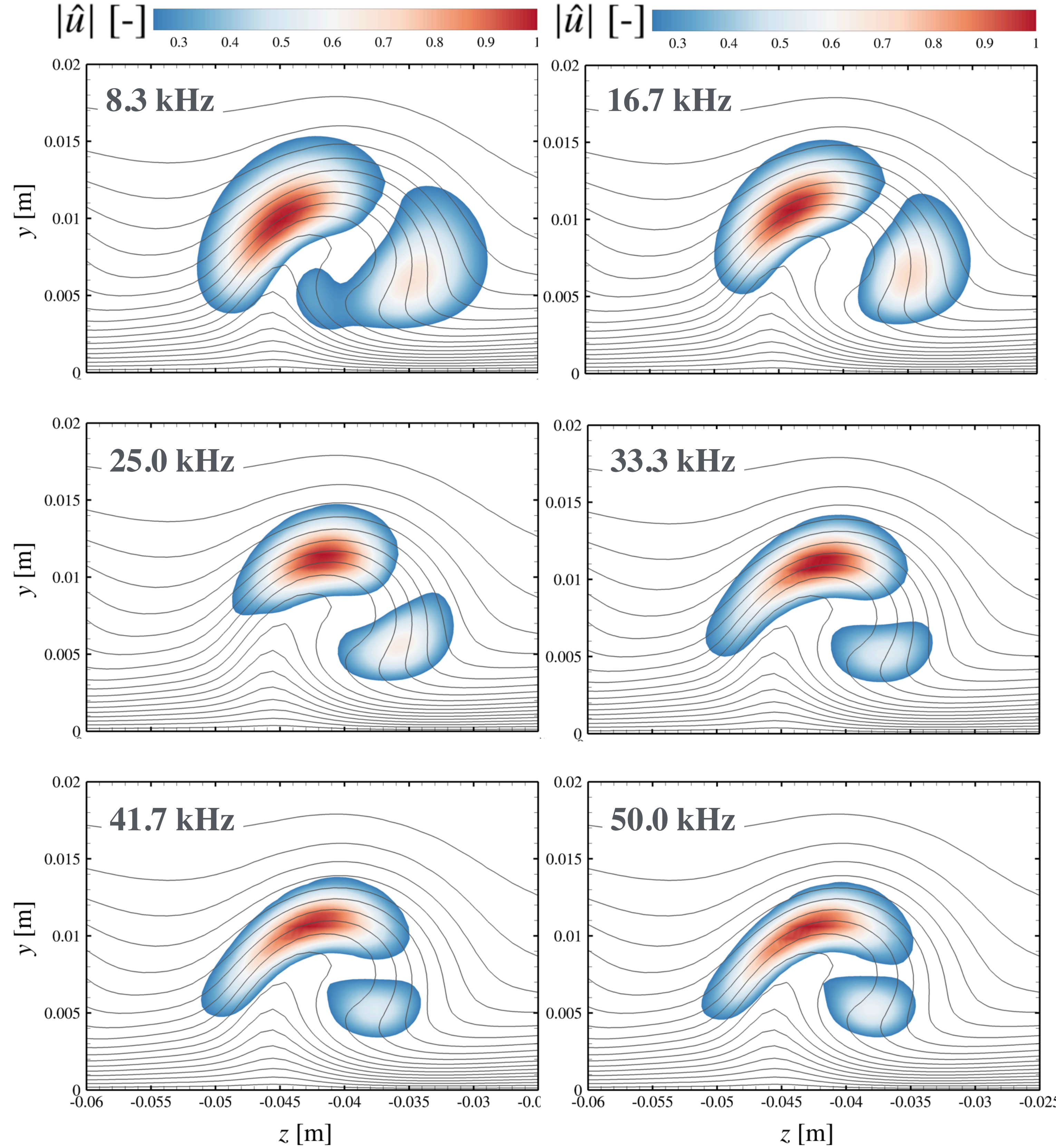




Velocity (left) and temperature (right) profiles at the roughness position for different gas models

Modes of Instability





$$N = \int_{x_0}^{x_1} \sigma \mathrm{d}x$$

σ : Disturbance growth rate

Investigations under Re-entry Conditions: Summary[3]

a. Velocity profiles are not significantly affected by inclusion of *non*-equilibrium

b. Re_{kk} in case of *non*-equilibrium becomes larger than the one in case of equilibrium for sufficiently high roughness

c. Inclusion of chemical *non*-equilibrium has destabilizing effect

d. *y*-mode at low frequencies; *z*-mode at high frequencies,

f. *y*-mode more unstable (in the range of frequencies considered here)

[3] Di Giovanni & Stemmer: "Direct Numerical Simulations of roughness-induced transition in the boundary layer of a hypersonic spherical forebody under consideration of high-temperature gas effects", AIAA 2018-4046 (2018)

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Current investigations

a. Transition scenario with high-temperature gas effects

b. Investigations on more distributed-roughness geometries

[3] Di Giovanni & Stemmer: "Direct Numerical Simulations of roughness-induced transition in the boundary layer of a hypersonic spherical forebody under consideration of high-temperature gas effects", AIAA 2018-4046 (2018)