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

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Motivation

Apollo 12 Command Module, Virginia Air & Space Center
Project: Transition on Capsule Configurations
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- DNS
- High-Temperature Gas Effects
Analysis of the Smooth Configuration
Analysis of the Smooth Configuration

1\textsuperscript{st} Mode: extremely accelerated boundary layer
\[\rightarrow\] STABLE
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Crossflow: absence of spanwise velocity component
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Görtler: convex geometry
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Transient Growth: $N$-factors $< 3$
  $\rightarrow$ NEGLIGIBLE

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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)
Analysis of the Smooth Configuration

1st Mode: extremely accelerated boundary layer
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Crossflow: absence of spanwise velocity component
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Görtler: convex geometry
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Transient Growth: $N$-factors $< 3^1$
   —> NEGLIGIBLE

—> Roughness-induced transition

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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)
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

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   Spanwise periodic roughness elements

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

   Random distributed roughness
   Base Flow
   Stability Analysis
Geometry and Freestream Conditions

Geometry: capsule-like hemisphere

Conditions: Hypersonic Ludwieg tube Braunschweig (HLB)

Gas model: ideal gas

<table>
<thead>
<tr>
<th>Medium</th>
<th>$M$</th>
<th>$T_0$ [K]</th>
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<th>$Re_{\infty}$ [1/m]</th>
<th>$R$ [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>5.9</td>
<td>470</td>
<td>295</td>
<td>$18 \cdot 10^6$</td>
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**TABLE 1.** Simulation parameters - windtunnel conditions
Analysis of a “simple” Roughness
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simple rgh: \( k = 100 \, \mu m \quad k/\delta = 0.35 \quad Re_{kk} = u_k q_k k/\mu_k = 400 \)
Analysis of a “simple” Roughness

- Counter-rotating vortices originate in the roughness wake
- Roughness wake decays rapidly
Analysis of a “simple” Roughness

- Counter-rotating vortices originate in the roughness wake
- Roughness wake decays rapidly
- $N$-factor $= \log(A_{\text{max}}/A_{\text{in}}) \sim 8$ (included roughness)

Amplitude of the roughness wake

Growth rate (disturbance at 250 kHz)
Definition of a \textit{distributed} Roughness
Definition of a *distributed* Roughness

**distrib rgh:**  \( k = 100 \ \mu m \quad k/\delta = 0.35 \quad Re_{kk} = u_k \rho_k k/\mu_k = 400 \)

**simple rgh:**  \( k = 100 \ \mu m \quad k/\delta = 0.35 \quad Re_{kk} = u_k \rho_k k/\mu_k = 400 \)
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
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

- 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)

Results of the Spatio-Temporal Fourier Analysis

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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Simulations at Re-entry Conditions

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**TABLE 2.** Simulation parameters - re-entry conditions
Simulations at Re-entry Conditions

Different simulations are run with 3 different gas models:

1. gas in chemical equilibrium (CEQ) $(T > 2000 \text{ K})$

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2. gas in chemical NON-equilibrium (CNEQ) 
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\[ \text{N}_2 \quad \text{O}_2 \quad \text{N} \quad \text{O} \quad \text{NO} \quad \text{N}_2 \]
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Different simulations are run with 3 different gas models:

1. gas in chemical equilibrium (CEQ) 
   \( T > 2000 \text{ K} \)

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)

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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

\[ N = \int_{x_0}^{x_1} \sigma \, dx \]

\( \sigma \) : Disturbance growth rate
Investigations under Re-entry Conditions: Summary

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)

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Current investigations

a. Transition scenario with high-temperature gas effects

b. Investigations on more distributed-roughness geometries