Development of advanced hypersonic models for transition to turbulence

Uncertainty Quantification for Transition prediction

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Introduction

Why Transition is crucial in Hypersonic?

- Planetary reentry/entry vehicles need safely designed heat shield (Fig. 1);
- Turbulent heat transfer up to five time higher than the laminar heating rates (Fig. 2);

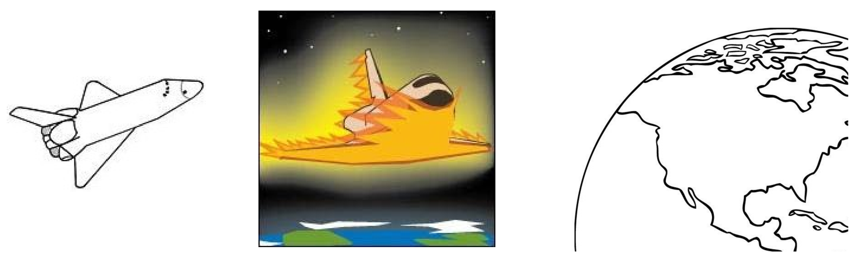

Figure 1 : Schematic representation of the physics of reentry

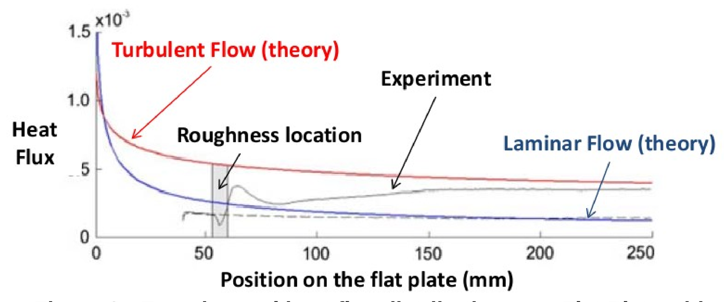

Figure 2 : Experimental heat flux distribution on a Flat Plate with a roughness element (P0 = 31 bar, T0 = 500 K, M = 6) [6]

What is the current approach in design?

- Safety factors to take into account "limited knowledge" on transition;
- Success of the mission guaranteed at the expense of the mass/payload;

State of the art

How Transition is now studied and predicted?

- Experiments : correlation and empirical transition criteria successfully used in design *but* expensive, limited operating times and conditions are not those of real flight;
- *CFD* : simulations of real operating conditions *but* lack of reliable transitional models for high Mach number (*M*>5), *DNS* expensive for design;
- Flight tests : very expensive, unfeasible for design;

Objectives

What is our goal?

- Uncertainty Quantification (*UQ*) to characterize the impact of "limited knowledge" and to establish "error bars" on quantity of interest, such as the heat flux;
- define margins for more confidence and less conservative design;
- determine uncertainties on free stream conditions (Mach number, Pressure, Temperature) or related to the geometry (surface irregularities, leading edge shape);

Strategy & Methods

What is Uncertainty Quantification?

- a probabilistic approach to simulate a system by taking into account all uncertainties on boundary, initial conditions and model parameters;
- uncertainties modeled with probabilistic distributions according to the expected values or experimentally based;
- propagation of the uncertainties to study the impact on the *Quantity of Interest* (*QI*) of the simulation (heat flux, skin friction distribution) ;

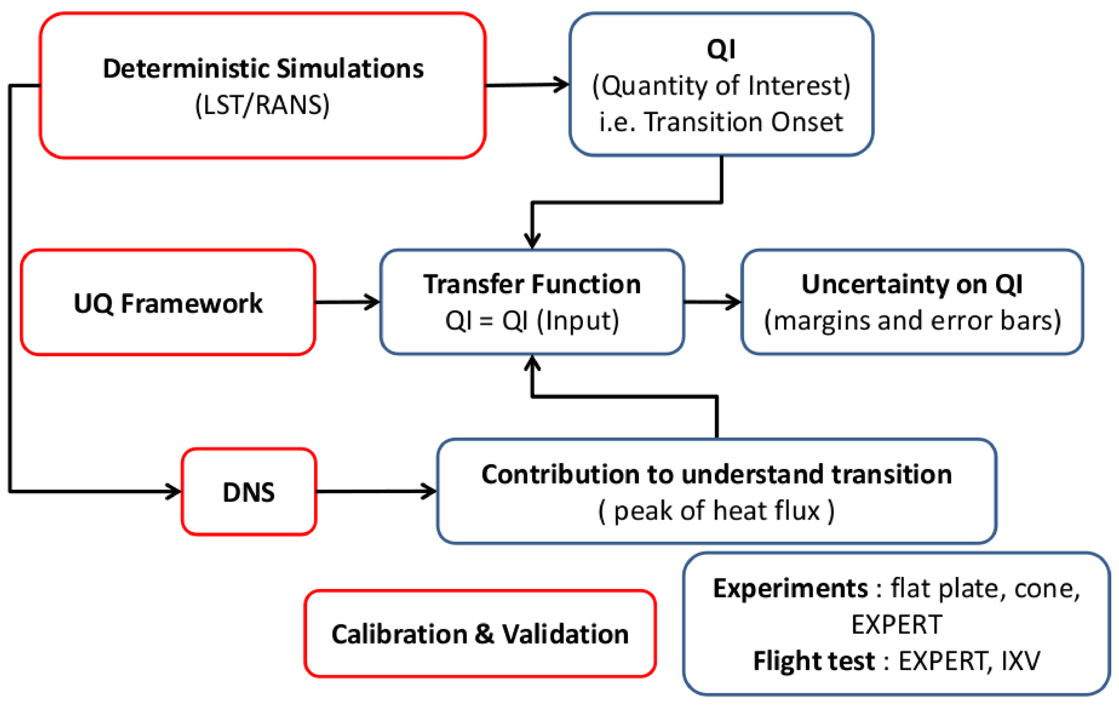

Figure 3 : Flow chart of the strategy proposed for the transition prediction

What is the Strategy?

1. Deterministic Simulations (LST/RANS) : case dependent random parameters (Frequency, propagation angle, leading edge radius) representing the input uncertainties;
2. Evaluation of the *QI* : i.e. rising of heat flux/skin friction distribution for the transition onset;
3. Relation *QI = QI (Input Parameters)* : Transfer Function (*TF*) to relate Input/Output;
4. UQ analysis : Monte Carlo, Polynomial Chaos samplings on the physical space to obtain the related *QI* via the *TF*;
5. Definition of *"error bars"* and uncertainty on the QI;
6. Investigation through *DNS* of relevant cases;
7. Calibration & Validation : experiments and flight data;

Preliminary Results

Transition prediction for the oblique breakdown mechanism in supersonic boundary layers

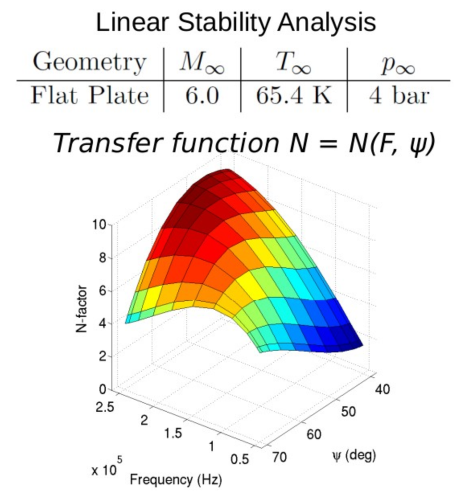

Figure 4 : Transfer function on a Mach 6 flat plate (Re = 4MiL)

1. Linear Stability Theory code (VESTA by Pinna F. [4]) to compute the N factor for different Frequency (*F*) and direction (*ψ*) of the oblique waves

- Transfer function : *N=N(F,ψ)* (Fig. 4)

2. Definition of the input uncertainties :

- Frequency and propagation angle spectra : *pdf* with normal distribution (Fig. 5)

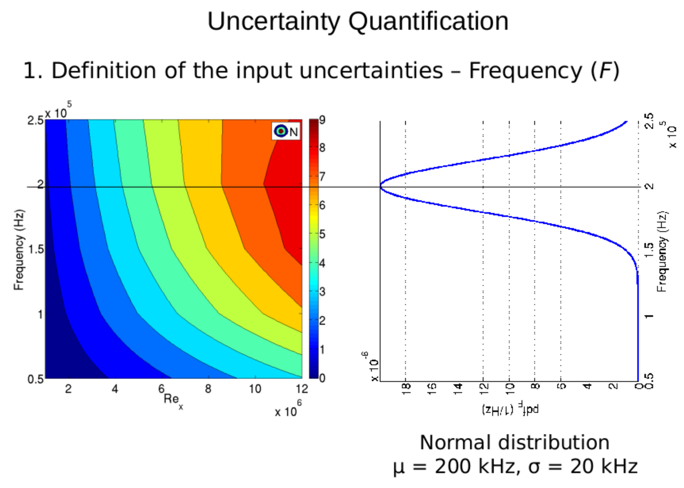

Figure 5 : *pdf* for the input uncertainties (Frequency)

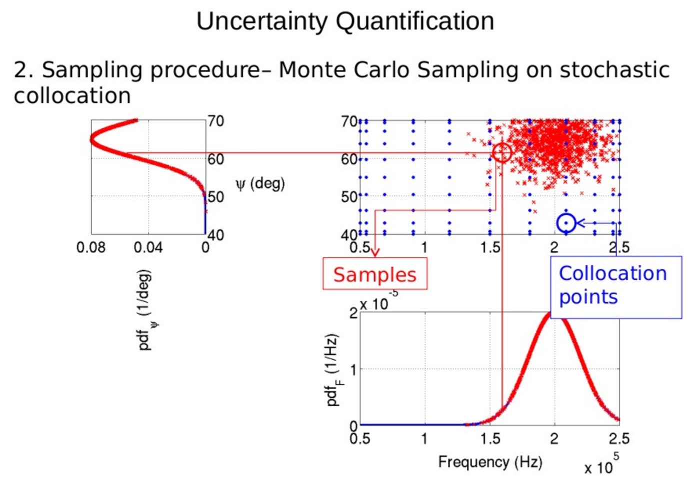

Figure 6 : Sampling procedure on the physical space according to input *pdf*

3. Monte Carlo sampling :

- each sample on the stochastic collocation space is related to the N factor according to the transfer function *N=N(F,ψ)* (Fig. 6)

4. Evaluation of the QI :

- the *pdf* of the output quantity of interest (N factor) is computed at each station of the domain (Fig. 7)

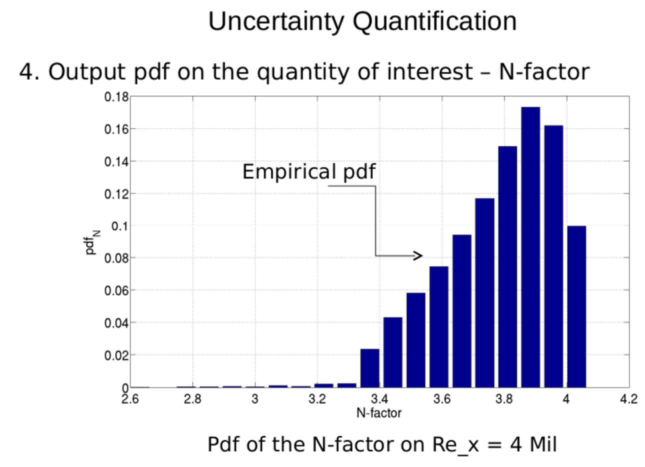

Figure 7 : *pdf* of the QI (N factor) at Re_x = 4 MiL

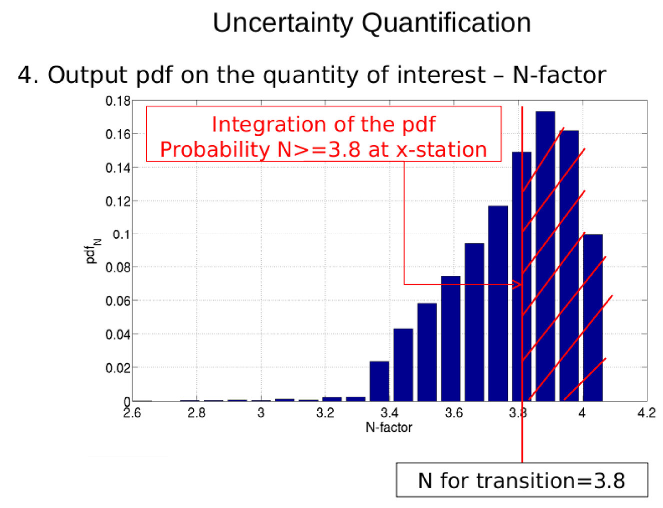

Figure 8 : Application of the trasition criteria on the N factor) at Re_x = 4 MiL

5. Transition Prediction:

- the *cdf* defines the probability of exceeding the threshold value for experimental transition (3.8 for the test case in [3]) at each station (Fig. 8)

6. Evaluation of probability of transition at each station and comparison with experimental results (heat flux distribution) (Fig. 9)

- possible interpretation of the probability as the intermittency factor (ɣ)

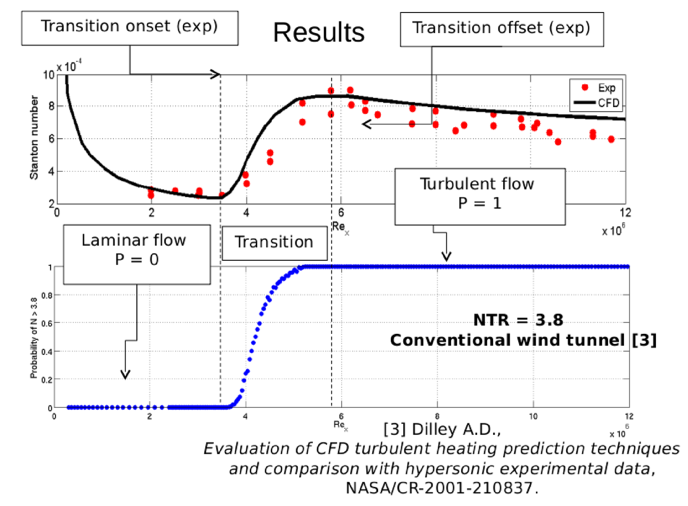

Figure 8 : Comparison between experimental data (red dots), RANS solver (Black line) and computed probability of transition (blue dots) for the Mach 6 flat plate test case [3]

Planning

- 1st year : Application of the methodology to experimental test cases (Flat Plate, Cone) with LST and RANS deterministic simulations;
- 1st & 2nd year : Inverse methodology to determine input uncertainties (probabilistic distributions) from experimental results;
- 3rd year : Improvement of understanding of transition mechanisms (DNS);
- 4th year : Calibration & Validation of the approach with experiments and flight data;

References

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[4] Pinna F., *Numerical study of stability and transition of flows from low to high Mach number, von Karman Institute for Fluid Dynamics*, Universita' "La Sapienza" di Roma, PhD thesis, 2012.
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