Development of Advanced Hypersonics Models for Transition to Turbulence: Uncertainty Quantification for Transition Prediction

Gennaro Serino

Aeronautics and Aerospace Department, von Karman Institute for Fluid Dynamics, Belgium, gennaro.serino@vki.ac.be

Supervisors: Thierry Magin♣ & Patrick Rambaud♠

♣*Assistant Professor* & ♠*Associate Professor, Aeronautics and Aerospace Department, von Karman Institute for Fluid Dynamics, Belgium, magin@vki.ac.be., rambaud@vki.ac.be*

University Supervisor: Vincent E. Terrapon

Professor, Aerospace and Mechanical Engineering Department, Université de Liège, Belgium, vincent.terrapon@ulg.ac.be.

Abstract

Transition has a crucial role in hypersonic applications. During an atmospheric reentry, transition increases the aerodynamic heating of the space vehicle thus compromising the integrity of the heat shield.
A new method for transition prediction is proposed by using Uncertainty Quantification (UQ) in numerical simulations. UQ aims at simulating a system by taking into account all the uncertainties due to its physical variability and to the hypothesis used in the mathematical models.
Preliminary results on a Mach 6 flat plate shows good agreement with experimental transition location detected via the heat flux distribution.

Keywords: Laminar to turbulent transition, Hypersonic, Uncertainty Quantification (UQ), Computational Fluid Dynamics (CFD)

1. Introduction

Simulations of aerospace applications are challenging problems involving many complex physical phenomena ; for instance, predicting the response of thermal protection materials to extreme reentry conditions involve flow transition from laminar to turbulent and aerothermochemistry. Reliable predictions of such complex systems require sophisticated mathematical models to represent the physics and phenomena such as transition. A systematic and comprehensive validation, including the quantification of uncertainties inherent in such models, is required.
Conventionally, engineers resort to safety factors to account for uncertainty parameters and to determine the quantities of interest, such as the heat shield thickness. These factors allow to avoid space mission failure and ensure safety of the astronauts and payload, but this is at the expense of reduced mass of embarked payload. Uncertainty Quantification (UQ) is a systematic approach to establish “error bars“ on quantities of interest, such as the heat flux, yielding to the design of the heat shield with more confidence. At the interface of physics, mathematics and statistics, UQ tools are still in constant development in computational science. These tools aim at developing rigorous methods to characterize the impact of “limited knowledge“ on the quantities of interest.
We propose to develop a UQ methodology to study transition from laminar to turbulent in hypersonic flows. Moreover, the methodology that we propose to develop will be general and can be applied to many other research topics such as flow transition in turbo machinery.

2. Objectives

The project general goal is to propose a new approach in transition prediction. In order to achieve this goal, it will be necessary to also improve our understanding of transition mechanisms in hypersonic flows. A variety of tools will be used to model turbulence (DNS, RANS, e^N, PSE) and coupled with UQ in order to yield a reduced model suitable for engineering applications. All uncertainties and errors will be taken into account in order to define the design margins for space vehicles. The uncertainties will comprise the free stream conditions (Mach number, pressure, temperature, turbulence intensity), surface parameters (roughness element height), transition model parameters and wall chemistry models, in order to investigate a wide range of cases including natural and bypass transition.

3. State of the art

One of the most critical tasks in the design of space vehicle is the prediction of transition from laminar to turbulent flow. Transition depends on several parameters and, in particular, it is promoted by the presence of surface unevenness as roughness, steps, gaps and ramps (Fig.1). A sound transition model valid in the hypersonic regime is still lacking.

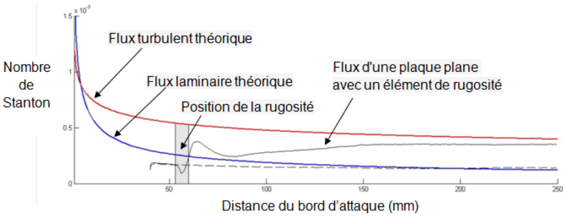

Figure 1: Theoretical(blue and red lines)-experimental(black line) comparison of the heat flux on a flat plate with a ramp roughness element (P_0 = 31 Bar, T_0 = 500 K, M = 6) [29].

Experimental investigations in hypersonics are quite expensive and they can be only be performed in short times and for limited operating conditions. CFD allows to simulate a wide range of conditions even if there are difficulties to model and predict transition at high Mach number. Models include Wilcox's procedure to use the low-Reynolds number $k-\epsilon$ model, reported in [4], as a transition region model where a roughness strip is used to fix the transition point. Schmidt and Patankar's production term modifications for low-Reynolds number $k-\epsilon$ models is an attempt to solve the problems these models have in simulating the transition region. Moreover, Warren, Harris and Hassan [5] developed a one equation turbulence model that accounts for the first and second mode disturbances in the transition region. Other models that can be considered include the algebraic transition region model of ONERA/CERT and the linear combination model of Dey and Narashima [6]. An interesting approach is the eddy viscosity-intermittency transition model ($R-\gamma$) which is based on the work of Ryong Cho and Kyoon Chung [7]. The model exploits the transport equation for the eddy viscosity (R) of Goldberg's one-equation turbulence model reported in [8] that is similar in form to the model of Spalart-Allmaras shown in [9]. The model was applied in [10] by the author for roughness induced transition prediction in hypersonic flows. The model was able to correctly predict the onset of transition even though all the physical processes (vortices and flow topology) were not completely reproduced.
In conclusion, these methods fail because of 3 reasons: conditions vary for each particular mission, random nature of transition (uncertainty in free stream turbulence, surface unevenness), simple models do not reflect all the physical processes. UQ is the strategy which aims to investigate the effects of those uncertainties in numerical simulations with a probabilistic approach.

4. Scientific strategy

4.1. Role of Uncertainty Quantification in predictive simulation

UQ allows to simulate a system by taking into account all uncertainties regarding the boundary, initial conditions and the model parameters.
All the uncertainties are modeled with a distribution which resembles the expected behavior of the considered variable. Each distribution is then modulated with a transfer function to obtain the output quantity of interest. We will calculate how the quantities of interest are influenced when the random variables describing the sources of uncertainties take different values. We therefore study how the uncertainties "propagate" through the simulations.
The most common approaches in propagation are the Monte Carlo method and the polynomial chaos method [12]. With respect to conventional sensitivity approaches, UQ offers the possibility to take into account the effect of statistical distributions in numerical simulations.

4.2. Methodology

The novelty of the approach consists in using UQ in numerical transition prediction. Simulations will be carried out with a case-dependent random parameter which, for instance, will mimic the uncertainty of the disturbance spectrum. The probabilistic distributions as well as the range of variations of the variables will be based on experimental data. Once these parameters will be selected, numerical simulations will be performed and a quantity of interest will be computed to evaluate the effects of the parameters. This quantity can be the stream wise location of increase in skin friction or in heat transfer, which may be regarded as representative of the transition location. Several independent simulations will be performed in order to use, for example, a Monte-Carlo sampling to build the response approximately, as an interpolant of a response surface (the collocation points), using a Lagrange polynomial. Several research codes developed at the VKI will be used in the proposed research.

- Simulations will be carried out with a Reynolds Average Navier Stokes (hereafter RANS) and a Linear Stability Theory (hereafter LST) codes. UQ on LST codes [24] will be used to investigate the onset of transition. UQ on RANS codes will be used to determine both the onset of transition and the successive turbulent flow. Turbulence models based on different transport equations will be used in order to obtain different transfer functions. This will contribute to complete the lack of knowledge derived by using such approximations and to reduce the uncertainties due to the models.

- Direct Numerical Simulations (DNS) will be used to investigate some interesting cases highlighted with the RANS/LST simulations. For instance, RANS models predict transition by switching the solution from laminar to turbulent flow. Experimental results showed that, when transition occurs, the skin friction and the heat flux distribution are characterized by an overshoot immediately following its onset (Fig.1). RANS models are not capable of reproducing such an overshoot so that a further investigation is necessary by performing DNS on limited zone of interest with the codes mentioned in [20] and [21].

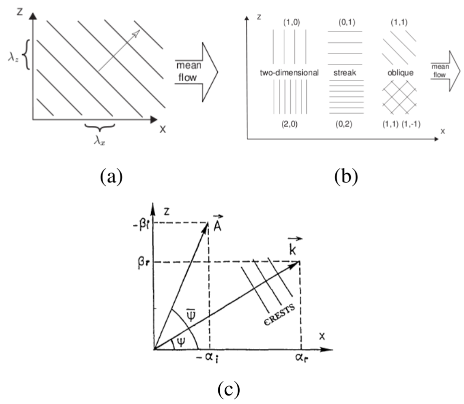

Figure 2: (a)Wave propagating in the mean flow with streamwise wave number λ_x and spanwise wave number λ_z, (b)Examples of notation for wave disturbances[13], (c) Notation for the oblique waves

- The strategy and the conclusions derived by test cases will be used for the final validation case and for the eventually application of the inverse problem. This will be the EXPERT re-entry vehicle configuration. A wide experimental database based on wind tunnel tests is available which will give important contribution to investigate real flight conditions with the proposed methodology.

5. Application

The methodology is currently applied in transition prediction for the oblique breakdown mechanism occurring in supersonic boundary layers. In this case, the LST code VESTA, developed at the VKI by Pinna [24], is used to compute the linear amplification of oblique waves on a Mach 6 flat plate. The code is used to compute the N factor for the e^N transition prediction method in order to detect the transition location on the flat plate to be compared with experimental data. The linear stability is coupled with the UQ which consists in assigning an uncertain spectrum, that is a probability density function (pdf), to the frequency and to the propagation angle of the oblique waves traveling inside the domain(Fig. 2).

Then, the quantity of interest, that is the N factor, is computed at each location as a 2D function dependent on both the frequency and the wave angle. Results of the LST are then sampled by using a Monte Carlo method to compute the main statistical moments of the quantity of interest. The criterion for transition is the N factor experimentally determined in the facility where the test has been carried out. Finally, the probability of transition is computed at each station on the flat plate as the probability of having the computed N factor exceeding the threshold value given by experimental results as represented in Fig.3.

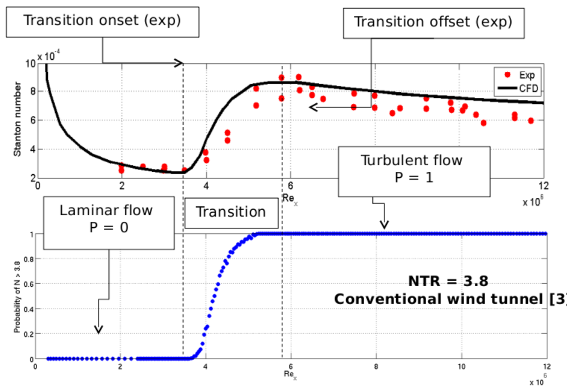

Figure 3: Comparison between experimental data (red dots), RANS solver (black line) and probability of transition (blue dots) for the Mach 6 flat plate test case in [27]

6. Conclusions

A probabilistic transition prediction methodology is proposed by combining numerical simulations and Uncertainty Quantification. Results on test case concerning a hypersonic flat plate demonstrates the agreement with experiments in terms of transition onset location. Good agreement was achieved on the transition point but the prediction of transition offset occurs slightly before experimental value thus the numerical transition length is shorter than in the experiments. Comparison is made between the probability of transition (N-factor greater than the threshold value for transition) and the experimental/computed heat flux distribution. It is possible to infer a parallel between the computed probability and the intermittency since the range of variability is the same [0,1] and also the physical meaning, since the intermittency is defined as the turbulent-laminar time ratio. Further investigation will involve a second test case on a 5° sharp and blunt cone. Preliminary results are promising and it will be interesting to determine in future work the impact of the methodology on simulations of higher complexity as RANS, with transitional models, and DNS.

Acknowledgments

The author gratefully acknowledges the “Fonds de la Recherche Scientifique” for the FRIA fellowship which is financing the current doctoral research.

References

[1] H. Schlichting, Boundary Layer Theory, Springer, 1995.

[2] Anderson J.D., Hypersonic and High Temperature Gas Dynamics, AIAA, 1986.

[3] R.D. McDaniel, R.P. Nance and H.A. Hassan, Transition Onset Prediction for High-Speed Flow, Journal of Spacecraft and Rockets, vol. 37 n3, 2000.

[4] Wilcox David C., Turbulence Modeling for CFD, DCW Industries, 1993.

[5] Warren E., Harris J. and Hassan H., A Transitional Model for High Speed Flow, AIAA-94-1851-CP, 1994.

[6] Narashima R., The Laminar Turbulent Transition Zone in the Boundary Layer, Progress in Aerospace Science,vol.22, pages 29-82, January 1985.

[7] Ryong Cho Ji, Kyoon Chung M., A $k-\epsilon$ Equation Turbulence Model, Journal of Fluid Mechanics, vol.237, pages 301-322, 1992.

[8] Goldberg U., Turbulence Closure with a Topography-Parameter-Free Single Equation Model, International Journal of Computational Fluid Dynamics, vol. 17. pages 27-38, 2003.

[9] Spalart,P.R., Allmaras,S.R., A one equation turbulence model for aerodynamic flows, American Institite of Aeronautics and Astronautics (AIAA), vol. 92-0439, 1992.

[10] Serino G., Numerical prediction of transition in hypersonic flow, von Karman Institute for Fluid Dynamics, DC report 2011.

[11] Malik, M. R., Hypersonic flight transition data analysis using parabolized stability equations with chemistry effects, Journal of Spacecraft and Rockets 40 (3), 332, 2003.

[12] G. Iaccarino, T. Chantrasmi, A. Doostan, Towards Uncertainty Quantification in High-Speed Turbulent Flow Simulations, Stanford PSAAP Center - UQ Workshop - July 2008.

[13] Berlin, S., *Oblique Waves in Boundary Layer Transition*, Doctoral Thesis, Stockholm, 1998.

[14] Marco Panesi, Kenji Miki, E. Prudencio, Serge Prudhomme, Quantification of Uncertainty in Hypersonic Flows, RTO-AVT-VKI short course on Uncertainty Quantification, Stanford University, California, 2010.

[15] Ioana Cozmuta, Uncertainty Quantification and Statistical Engineering for Hypersonic Entry Applications, RTO-AVT-VKI short course on Uncertainty Quantification, Stanford, CA, 2011.

[16] Ren Pecnick, Jeroen A.S. Witteveen, and Gianluca Iaccarino, Uncertainty quantification for laminar-turbulent transition prediction in RANS turbomachinery applications, AIAA 2011-660, Orlando, Florida, 49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition 4 - 7 January 2011.

[17] S.C.Tirtey, O.Chazot, L.Walpot, Characterization fo hypersonic roughness-induced boundary-layer transition, PhD Thesis, von Karman Institute for Fluid Dynamics, 2010.

[18] Magin, T. E., A model for inductive plasma wind-tunnels, Ph.D. thesis, von Karman Institute for Fluid Dynamics, Rhode-Saint-Gense, 2004.

[19] Marxen, O., Iaccarino, G. & Shaqfeh, E., Disturbance evolution in a Mach 4.8 boundarylayer with 2-D roughness-induced separation and shock, Journal of Fluid Mechanics, in press, 2009.

[20] Marxen O., Iaccarino G., Shaqfeh S.G., Boundary-layer transition via spatially growing oblique waves, Center for Turbulence Research, Stanford University, Under consideration for publication in Journal of Fluid Mechanics, 2009.

[21] Marxen O., Iaccarino G., Shaqfeh S.G., Uncertainty quantification for linear and weakly non-linear supersonic boundary-layer instability, Center for Turbulence Research, Stanford University, Annual Research Briefs 2009, 2009.

[22] Marxen O., Iaccarino G., Instabilities in supersonic boundary layers in the presence of uncertainty, Center for Turbulence Research, Stanford University, 2009.

[23] Iaccarino G., Magin T., Prudhomme S., Abgrall R., Bijl H., RTO-AVT-VKI Short Course on Uncertainty Quantification, Bruges BE, May 13-14, 2011.

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

[25] Arnal D.,Special Course on Progress in Transition Modeling, AGARD report 793, 1993.

[26] Horvath T.J., Berry S.A., Hollis B.R., Chang C.L. and Singer B.A., Boundary layer transition on slender cones in conventional and low disturbance Mach 6 wind tunnels, NASA Langley Research Center, AIAA 2002-2743.

[27] Dilley A.D.,Evaluation of CFD turbulent heating prediction techniques and comparison wit hypersonic experimental data, NASA/CR-2001-210837.