# Uncertainty Quantification and Robust Design in Turbomachinery

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Virtual prototyping (VP) is a key technology for environmental friendly and cost effective design in the aircraft industry. However, the underlying analysis and simulation tools, are currently applied with a unique set of input data and model variables, although realistic operating conditions are a superposition of numerous uncertainties under which the industrial products operate (uncertainties on operational conditions, on geometries resulting from manufacturing tolerances, numerical error sources and uncertain physical model parameters).
Major new developments in this new scientific area of Uncertainty Management and Quantification (UM and UQ) and Robust Design Optimization (RDO) are currently developed to bridge the gap towards industrial readiness.
The lecture will cover applications of recent developments to UQ and RDO applied to turbomachinery.

A key concern in both UQ and RDO is how to handle large number of simultaneous uncertainties including generalized geometrical uncertainties within a quantifiable objective of a turn-around time acceptable for industrial readiness. A series of different methodologies are available and successfully assessed on a unique database with prescribed uncertainties, which was built from industrial challenges provided by the UMRIDA (<u>U</u>ncertainty <u>M</u>anagement for <u>R</u>obust <u>I</u>ndustrial <u>D</u>esign in <u>A</u>eronautics) project. The project allowed to raise the Technology Readiness Level for various methodologies for UQ and RDO from a basic level 2-3 to an industrial applied level of 5-6, demonstrated by the application of the developed methods to the industrial challenges form the UMRIDA database while respecting the quantifiable object defined. The turn-around times of these methods are at the end of the project appropriate for use in daily engineering practice.

The analysis of non-deterministic simulations using a Non-Intrusive Probabilistic Collocation Method (NIPColM) is applied to Rotor 37 with up to 10 simultaneous geometrical and operational uncertainties, allowing also to define the relative sensitivities of the considered uncertainties.

An important industrial issue is the ***inverse design problem***, which aims at maximizing the manufacturing tolerances while keeping a small variability of the turbomachinery performances. This requires a methodology allowing the propagation of manufacturing uncertainties, based on a large number of correlated data to represent the manufacturing process, coupled with a Principal Component Analysis. The method is applied to the NASA Rotor 37, and a 1.5 stage high-pressure compressor, with correlated uncertainties on the blade geometry. The correlations are defined by an analytical function and the influence of each parameter of this function is investigated. It is shown that the modification of the amplitude of the variability allows defining an inverse robust design problem.

Finally a strategy for robust design optimization (RDO) is presented, i.e. optimization under uncertainties reducing the variability of the system output with respect to the input uncertainties. This strategy relies on the non-intrusive probabilistic collocation method for the uncertainty propagation and a surrogate assisted optimization strategy. In order to allow for RDO within reasonable turnaround times, a mixed Design of Experiments (DoE) is built, which comprises of design variables and uncertainties as individual dimensions. This reduces the cost by one order of magnitude compared to an approach where every point in the DoE is run with a UQ simulation. The robust design optimization problem is formulated as a simultaneous maximization of the mean efficiency and minimization of standard deviations of efficiency and of other global output quantities at the example of Rotor 37.

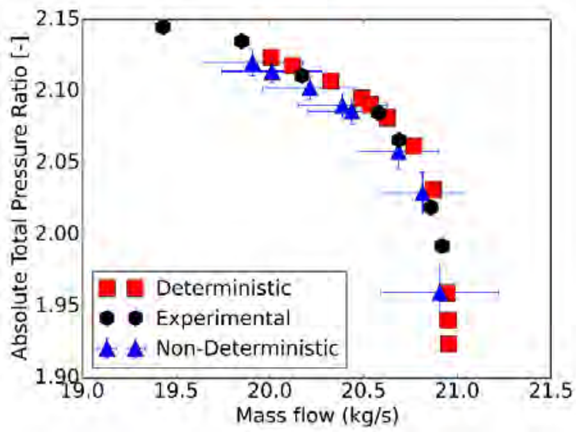


**Figure 1**: Non-deterministic absolute total pressure ratio plotted over mass flow with deterministic results and experimental data at the example of Rotor 37. UQ bars are $\pm\sigma$ .

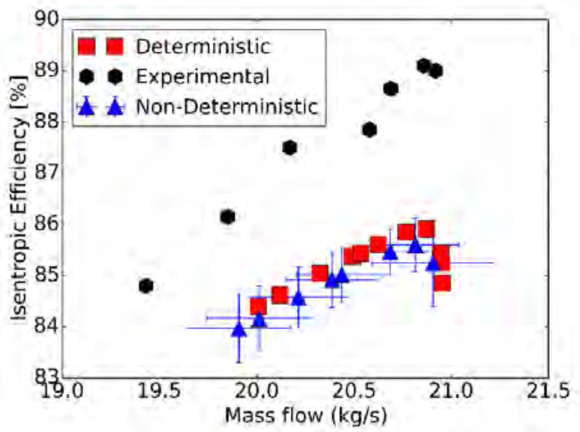


**Figure 2**: Non-deterministic isentropic efficiency plotted over mass flow with deterministic results and experimental data at the example of Rotor 37. UQ bars are $\pm\sigma$ .

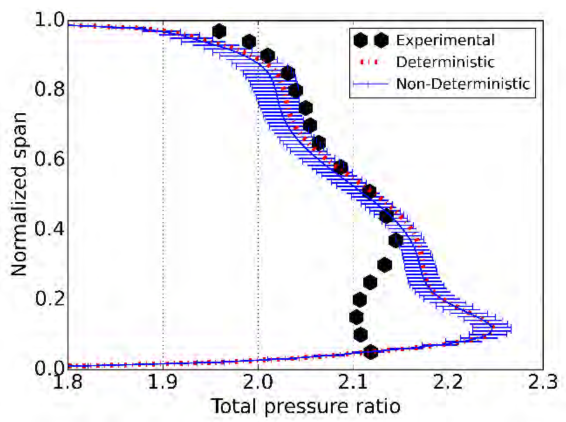


**Figure 3**: Non-deterministic absolute total pressure ratio plotted over normalized span at a downstream position of the rotor blade in comparison with deterministic results and experimental data at the example of Rotor 37. UQ bars are $\pm\sigma$ .

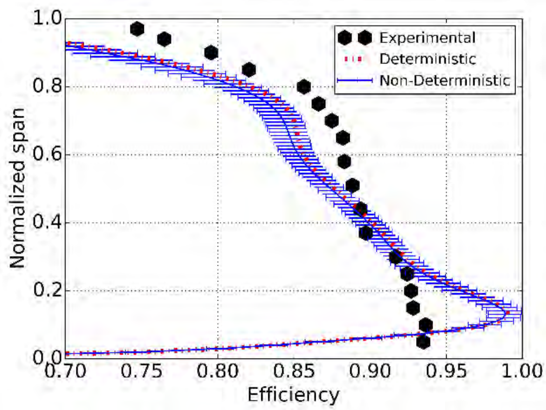


**Figure 4**: Non-deterministic isentropic efficiency plotted over normalized span at a downstream position of the rotor blade in comparison with deterministic results and experimental data at the example of Rotor 37. UQ bars are $\pm\sigma$ .

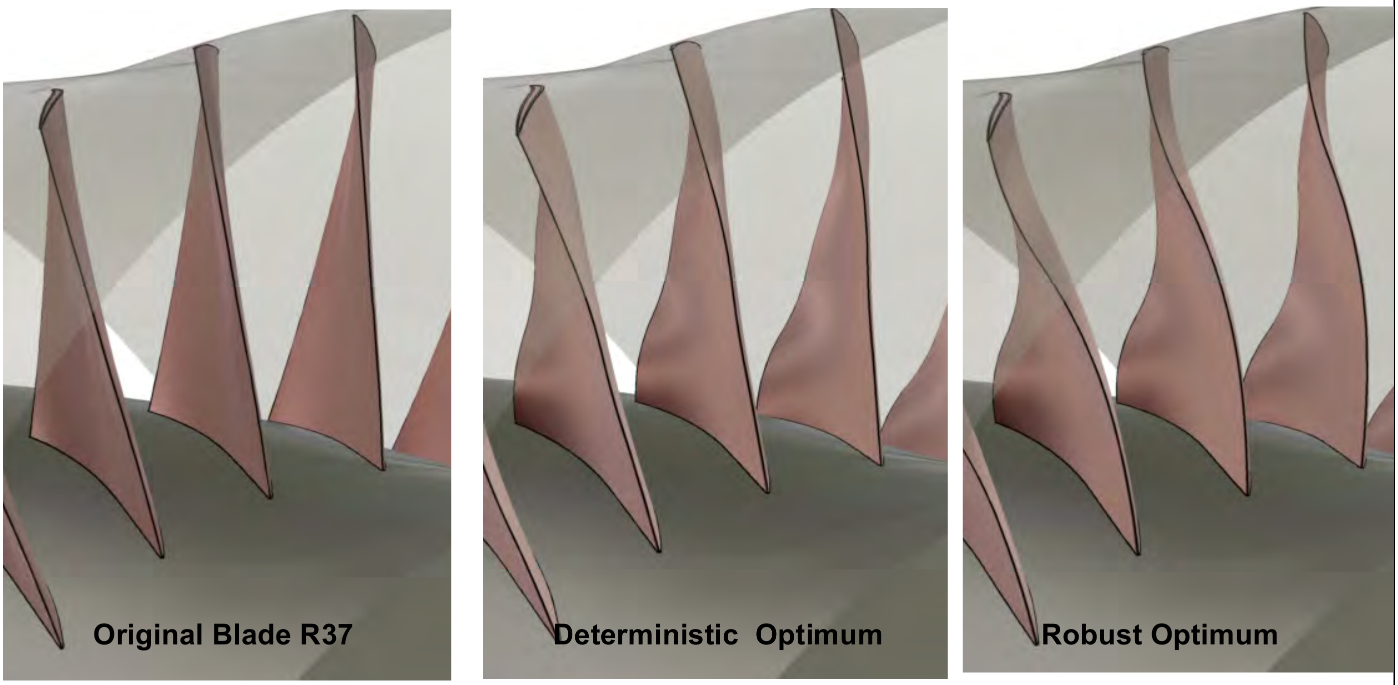


**Figure 5**: Results of a robust design optimization on Rotor 37

## Short Bio

Charles Hirsch is Professor Em. at the VRIJE UNIVERSITEIT BRUSSEL (VUB); Fellow of the Royal Flemish Academy of Belgium for Sciences and Arts; President and Founder of the CFD software company NUMECA International, a spin-off of the research activities in his Department of Fluid Mechanics at the VUB. He has written several books on CFD, 'Volume 1: *Fundamentals of Computational Fluid Dynamics*, 'Volume 2 : *Computational Models for Inviscid and Viscous Flow Models* and has over 20 book publications as Editor and over 500 Journal and Conference Publications.
He is the European Editor of the International Journal of Computational Fluid Dynamics.