Uncertainty in Design

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UTP for design

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Uncertainty

In recent years, there has been a resurgent interest in computational analysis and design methods that rationally accommodate uncertainty arising from sources such as system parameters, operating conditions, and modelling errors. The primary driving forces behind this development include the ever increasing requirement for robust engineering systems, and reducing reliance on full-scale testing for assessing system reliability. The uncertainty in inputs for any nondeterministic studies may be due to accepted approximations, the physics of the problem which cannot be modelled, incomplete knowledge aspects of the problem, or human induced errors, such as a lack of precision. In these cases, it is important to consider the uncertain inputs as random variables that may take on some prescribed distribution of values rather than a single precise value. These studies are known as nondeterministic analyses. The potential for input uncertainty, expressed in disciplinary analyses via distributions rather than single values, introduce a level of uncertainty in the resulting analysis outputs and raise the need to consider output distribution.

Why do we need Uncertainty?

The deterministic methods currently in use for product design either tend to over optimize or produce solutions that perform well at the design point but have poor off-design characteristics. There is a need for methods that provide accurate and efficient solutions to nondeterministic multidisciplinary aerospace vehicle design problems. Uncertainty based design methods can be employed to solve such problems.

Uncertainty Propagation / Analysis

The objective of uncertainty analysis (or propagation) is to characterize the uncertainties in the system output given some knowledge of the uncertainties associated with the system parameters together with one or more computational models or experimental data.
For realistic systems one must include uncertainties of various types in the mathematical model of the system. To use uncertainty-based design methods, the various uncertainties associated with the design problem need to be characterized and managed.
A wide variety of probabilistic uncertainty propagation techniques exist. The uncertainty propagation techniques generally fall into one of six categories: simulation methods, importance sampling techniques, first order reliability methods, second order reliability methods, response surface methods, and methods of moments techniques. The application of probabilistic methods requires the definition of
1. Random input variable probability models or distribution types
2. Response models that describe the physics, process, or rules which govern the system behaviour.
3. Models that predict the outcome of an event.
This is also shown in figure 1.

Fig. 1

Uncertainty in Compressor Blades

The performance and integrity of compressor and fan blades is central to the behavior of modern gas turbine engines and must thus be optimally designed. During operation, compressor and fan blades are exposed to foreign object damage (FOD) that lead to the pitting of the blade leading edges. Such phenomenon inevitably lead to degraded overall engine efficiency. The shape and the size of the damage caused, due to FOD, are uncertain in character. Hence, it is important to develop a probabilistic methodology for quantifying and mitigating the effects of FOD on the aerodynamic performance. Figure 2 shows the comparison between the Mach number distribution on a NACA0012 blade with and without FOD.

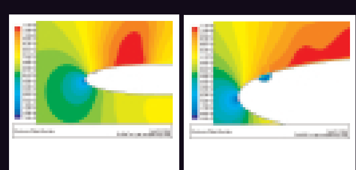

Fig. 2

Figure 3 shows the CL (Lift Coefficient) versus Alpha graph for both cases.

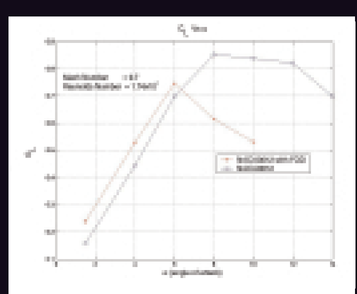

Fig. 3 CL Vs Alpha for aerofoil with and without FOD

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Future Work

Future work will be aimed at building design tools that would enable designers to examine and trade-off nominal and degraded performance while maintaining adequate structural strength. The erosion behavior would need to be examined using a probabilistic framework since erosion processes are not deterministically predictable. The aim would be to draw on existing multi-fidelity modeling experience, Response Surface Methodology (RSM) and Design of Experiment (DOE) techniques to deal with the inevitably demanding computational models that would need to be dealt with. The probabilistic nature of the damage process would be dealt with by using both Monte-Carlo and Bayesian surrogate models so that the uncertainty in these processes can be realistically and efficiently captured. This will involve a number of stages:
(1) Develop simplified random variable and more sophisticated random field models for characterizing the surface roughness and pitting of compressor blades using field data from Rolls Royce.
(2) Integrate and deploy CFD solvers on the Southampton computational grid for massively parallel Monte Carlo simulation of the effects of FOD on the aerodynamic characteristics.
(3) Develop efficient algorithms drawing on existing experience with adjoint CFD solvers, importance sampling, Bayesian response surface methodology, and physics-based surrogate modeling techniques to deal with the inevitably demanding computational models that would need to be dealt with.
(4) Formulate design optimization procedures that rationally take into account the important sources of uncertainties identified in the earlier phases. Study how initial design performance can be traded-off against life-management issues and robustness.

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