Fidelity Uncertainty Characterization Leading to Robust Design

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Abstract

Design Optimization & MDO studies carried out at CASDE, IIT Bombay are summarized. MDO architectures using WingOpt, effective use of low fidelity design thumb rules to shrink design space for S-Duct for a combat aircraft are briefly touched upon. Robust design of systems using low fidelity analysis tools and characterization of fidelity uncertainty using sparse high fidelity evaluations is discussed in detail.

Key Words: Robust design, Design Optimization, MDO

1 INTRODUCTION

Center for Aerospace Systems Design & Engineering (CASDE) was established in 1999 and initiated work in the area of Design Optimization and Multidisciplinary Design Optimization (DO/MDO) in 2000. CASDE has gained insights into issues and tools in DO/MDO [1] and also conducted several professional development courses in the area for practicing engineers [2]. Current research includes uncertainty characterization for robust design and systems design of aerospace vehicles.

2 AEROELASTICITY BASED MDO OF AIRCRAFT WING

Initial studies at CASDE were aimed at understanding of various generic MDO architectures discussed in the literature through a relatively complex Multidisciplinary aerospace sub-system. Aero-elastic design of wings offered an interesting problem for the same that generated insight into various MDO architectures [3]. The studies involved reformulation of the wing design problem through several different variants of existing single level generic architectures, specifically for coupled aerodynamic and structural optimization of wing, focused on static aeroelasticity. The design problem involved simultaneous optimization of the wing aerodynamic plan-form and section variables along with its structural sizing variables for minimum load carrying structural weight subjected to structural, aerodynamic, performance and geometric constraints. The associated Multi-Disciplinary Analysis (MDA) problem is a coupled solution of the state equations of the aerodynamic and the structural disciplines by nested iterations. The Multi-disciplinary Design Optimization (MDO) problem is posed as a three discipline coupled problem, with the trim (maneuver) process required to define structural design loads considered as a separate discipline. This lead to a number of interesting reformulations of the MDO problem based on (i) the reordering of the nested iterations and (ii) decoupling the nested iterations at different levels through the introduction of pseudo design variables and pseudo constraints. Formulation of six variants of the MDO problem and their implementation was presented along with computational issues related to convergence of the iterative processes. A special constraint based on a divergence control parameter has been formulated to indirectly handle the aeroelastic instability, without an explicit divergence eigenvalue constraint. Optimization results from the different formulations were compared to study their computational performance and bring out the impact of aeroelasticity on the design of the flexible wing.

3 S-DUCT DESIGN

S-Ducts are commonly employed in combat aircraft as part of engine air induction systems. They are required to meet air mass flow demands of engine with high pressure recovery and low distortion. While good estimates of pressure recovery is possible using low fidelity engineering methods, distortion requires high fidelity CFD analysis. Short design cycle for CFD based design of 3D Ducts is hence extremely useful and forms the motivation for this work. Design methodology [4]

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SAROD-2005
Published in 2005 by Tata McGraw-Hill

for 3D-Ducts uses a mixture of design thumb rules, low fidelity analysis (LFA) and high fidelity analysis (HFA). Thumb rules identify good ducts that are likely to be free of pockets of flow separation and LFA estimates pressure recovery. A simple optimization problem that maximizes LFA pressure recovery subject to thumb rules that ensure separation free ducts defines a base line duct. Commercial CFD software FLUENT is used for HFA analysis. A grid sensitivity analysis is performed on the baseline duct to determine the minimum grid size required to capture the flow solution and distortion coefficient, DC60 appropriately. This is essential to strike a proper balance between the conflicting requirements of lower simulation times and the desired accuracy levels. 60 longitudinal sections with 6634 cells at each section that have a total of 398,040 cells is chosen. FLUENT and its pre-processor GAMBIT are harnessed to provide requisite automation. Difficulties related to good gradients do not allow direct coupling of the automated CFD analysis to a gradient based optimizer, and instead surrogate based approach is used. Design space is reduced by exploiting LFA thumb rules to identify good ducts. Sampling is performed in the reduced design space only. Initially 12 samples are chosen for CFD analysis. A DACE [5] model is built for DC60 values at these 12 points. Further sampling is driven by the need to reduce relative error (prediction error/value) everywhere to less than 5%. An additional 9 samples were required to realize this. DACE surrogate model using 21 samples was used for defining the HFA based optimum duct. LFA based optimum duct that formed the baseline had DC60 of 6.91 and HFA optimization reduced this to 1.70. A Linux based cluster of 8 nodes (each node with PENTIUM IV 1.6GHz processor with 1 GB RAM) was used for this study. A single run of FLUENT using 4 nodes took around 30 hours for each run. Overall design took 630 hours of CPU time.

4 FIDELITY UNCERTAINTY CHARACTE-RIZATION LEADING TO ROBUST DESIGN

Computer simulation based design processes are being extensively used in preliminary design phase of complex aerospace vehicles like scramjet powered hypersonic vehicles. Analysis tools of varying fidelity are generally used to assess the system performance metrics. Often there is a constraint on the number of simulations using high fidelity analysis tools to predict the performance metrics, due to attendant computational demands. Hence the designer is confronted with the challenge of taking decisions in an environment wherein uncertainty is ever present. It is important here to distinguish between variability and uncertainty. Variability [6] is inherent randomness in the system. The use of probability theory to represent variability is well established. Uncertainty is defined as a potential deficiency in any phase or activity of the modeling process that is due to lack of knowledge. Uncertainty may also arise when there is a scarcity of high fidelity information. This is true when new classes of systems like scramjet powered hypersonic vehicles are being developed and no historical database exists. Probabilistic approaches to handle uncertainty in lieu of replacing the expensive high fidelity analysis with low/medium fidelity analysis and their application in design scenarios have been demonstrated recently. Quantification of uncertainty using a Bayesian approach to update the uncertainty model was proposed by Mantis [7] in the context of an aerospace design. Charania et al [8] used engineering methods for various participating disciplines in the design of Reusable Launch Vehicle together with a multiplier coefficient that is characterized by assuming a probability distribution. A probabilistic design approach for hypersonic vehicle has been also demonstrated by Umakant et al [9]. In this study, the effect of fidelity uncertainty on a disciplinary metric namely mass flow capture of air was propagated onto a system metric namely thrust deliverable and a design that maximized the system metric was sought through formal optimization. However, there are several issues that remain to be addressed. Basically the development of a non-deterministic design process involves three major steps, namely:

1. Based on the information available, construct an input uncertainty model
2. Propagate the effect of disciplinary uncertainty onto system performance metrics
3. Assess the system performance and take design decision under uncertainty

In most of the studies, discussed above, the focus has been on the last two steps. An uncertainty model was assumed based on the disciplinary experts recommendation regarding the prediction accuracy of the low fidelity analysis or based on evaluating the analysis tool with respect to similar applications. For example, if the disciplinary expert declared that the low fidelity analysis was accurate within ±10%, then a normal distribution with normalized mean $\mu = 1$ and standard deviation $\sigma = 3.33\%$ is assumed. Based on four high fidelity observations for a disciplinary metric, namely mass flow capture of air, a Weibull distribution was constructed by the authors of this paper to represent the uncertainty in its estimation using the low fidelity tool. These four observations correspond to arbitrary points in the design space. Therefore it is required to ascertain the validity of the assumed probability distribution if another set of observations were used. The present study seeks to bridge this gap. A novel approach based on ranks is proposed by Umakant et al [10] to aggregate high fidelity information in a sequential and cost effective manner. Rather than trying to model the uncertainty for the entire design support, a high fidelity sample is sequentially aggregated from the regions where the expensive function is potentially attractive. Design points with low response value receive higher ranks while those with higher response values receive lower ranks. Based on this information, residue is estimated as the difference between the high fidelity response value and the corresponding low fidelity response value. Based on this data, a probabilistic model for the residues is then constructed. Uncertainty model for the estimation of expensive function is now defined as the low fidelity model complemented with probabilistic model of the residue and the model may be used to take robust design decisions. It may be noted that in the context of optimization (for minimization), the inaccuracy of the model in the regions where the function is relatively higher is not of much interest. Rank transformation of the response enables to introduce the preferential characteristics in the uncertainty model. The approach has been demonstrated to quantify the uncertainty in estimation of a typical disciplinary metric for hypersonic vehicle design, namely mass flow capture of air. The low fidelity tool is based on oblique shock theory and the high fidelity tool is based on inviscid CFD computations.

5 CONCLUSION

CASDE is engaged in Design Optimization/MDO studies related to aerospace vehicles. Several studies in this area have been successfully carried out in the last 5 years. Uncertainty characterization and robust design form the current research interests.

Acknowledgment

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