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**Uncertainty analysis and robust optimization for low pressure
turbine rotors**

Giulia Antinori

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As far as the propositions of mathematics refer to reality, they are not certain; and as far as they are certain, they do not refer to reality.

Albert Einstein

Abstract

Jet engine design requires an accurate analysis of uncertainty sources and of their effect on life and integrity of the parts. Fuel consumptions and noise emissions must be strongly reduced while fulfilling safety requirements. In order to comply with both requisites, the dependence of the system on uncertainty must be diminished. This has been achieved, until now, through the use of safety factors. However, the advent of high power computing now allows the usage of probabilistic methods to determine the effect of input variation on output variables.

The aim of this thesis is to develop a new and problem-adapted methodology, based on a combination of appropriate methods for the design and optimization under uncertainty of a low pressure turbine (LPT) rotor. The physical system is described and simulated through finite element methods (FEM).

The proposed approach is discussed via the following investigations: possible sources of aleatoric uncertainty in the design process are identified, for instance in engine-to-engine variations, in the manufacturing process and in ambient conditions. The effect of these variations on the responses is measured through sensitivity analysis and uncertainty quantification. The optimization is performed on a reduced design space, which is obtained from the sensitivity analysis. In order to include robustness in this optimization, different architectures are compared and the most efficient, in terms of computational time, is chosen.

The use of probabilistic methods provides the practitioner with extensive information on the system, which cannot be gained through the use of classical deterministic techniques. An optimal solution, which satisfies the safety requirements and is insensitive to variation in the design parameters, is obtained by including robustness in the optimization. The methods analyzed here are illustrated for two different cases. In the first, the secondary air system as standalone is presented. In the second, a coupled flow-thermomechanical model is analyzed for a steady state condition and a reduced transient mission, enabling the calculation of a probabilistic life prediction.

Zusammenfassung

Die Triebwerksauslegung verlangt eine genaue Analyse der Unsicherheitsquellen und deren Effekt auf die Lebensdauer und Integrität der Bauteile. Kerosinverbrauch und Lärmemissionen müssen stetig reduziert werden unter Berücksichtigung weiterhin hoher Sicherheitsanforderungen. Um all diesen Anforderungen zu genügen, muss die Abhängigkeit des Systems von Unsicherheiten reduziert werden. Bis dato wurden diese über die Verwendung von Sicherheitsfaktoren abgedeckt. Mittlerweile ist es aufgrund von HPC (high performance computing) möglich probabilistische Methoden heranzuziehen, um die Auswirkung von Unsicherheiten der Eingangsgrößen auf die Ausgangsgrößen zu quantifizieren.

Das Ziel dieser Arbeit ist es eine speziell auf das Design einer Niederdruckturbine (NDT) zugeschnittene Methode zu entwickeln, die in einer Kombination von Auslegungs- und Optimierungsmethoden, die Unsicherheiten berücksichtigt. Das physikalische System wird durch FEM-Modelle abgebildet. Potentielle Unsicherheitsquellen innerhalb des Auslegungsprozesses, wie beispielsweise Triebwerk-zu-Triebwerk Variationen, in der Herstellprozesskette und in Umgebungsbedingungen werden identifiziert. Die Auswirkungen der Variationen dieser Parameter auf das System werden anhand von Sensitivitätsanalysen und Quantifizierung der Unsicherheiten gemessen. Die Optimierung wird innerhalb eines reduzierten Auslegungsraumes, der anhand von Sensitivitätsanalysen definiert wird, durchgeführt.

Um Robustheit in der Optimierung zu berücksichtigen, werden verschiedene mögliche Architekturen verglichen und die in Bezug auf Rechenzeit effizienteste Methode schließlich ausgewählt.

Die Verwendung probabilistischer Methoden stellt umfangreiche Informationen über das System bereit, die nicht anhand von Sicherheitsfaktoren oder sonstiger klassischer deterministischer Techniken gewonnen werden können. Eine optimale Lösung, die sowohl Sicherheitsanforderungen erfüllt als auch unempfindlich auf Variationen der Auslegungsparameter reagiert, wird durch die Berücksichtigung von Robustheit in der Optimierung gewonnen. Die Ergebnisse sind für zwei unterschiedliche Fälle dargestellt: zunächst wird das Sekundärluftsystem (SAS) für sich betrachtet. Anschließend wird ein gekoppeltes SAS-thermomechanisches Modell analysiert - sowohl für einen stationären Fall als auch für einen reduzierten transienten Flugablauf - was die Berechnung einer probabilistischen Lebensdauer vorhersage ermöglicht.

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Dedicated to my fiancé.

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