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Interval analysis of the standard of adaptive cycle engine component performance deviation

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ABSTRACT

The deviation of engine component performance has great impact on the Adaptive Cycle Engine (ACE) overall performance and task adaptability. To make ACE performance reach the mission requirement, proper standard of component performance deviation (CPD) should be given in advance. In this paper, an approach based on the first order Taylor series expansion has been proposed and applied to set the standard of CPD without large amounts of calculation. This approach is an inversion process of the normal interval analysis and can take the distinction between the impacts of CPD indexes into consideration. Fifteen component performance parameters and four important operating conditions are investigated. The results show that the distinction between the impacts of CPD indexes and different operating conditions is obvious. Compared with setting uniform standard for all CPD indexes, this method can better utilize component characteristics and make the standard reasonable and economical. The standard of CPD can be derived within 10 times of off-design point calculation through this method, which is much less than 32768 times of calculation for the vertex method. This method is universal and can be applied to setting standard for the CPD of other type of gas turbine engines.

1. Introduction

Nowadays, the design objectives for new generation aircraft include wider flight regime and combat radius, lower R&D cost, multi-mission and so on [1]. To achieve these design objectives, the new generation aircraft engine should include these features: On one hand, it should have the turbojet feature such as higher specific thrust to realize supersonic cruising and transonic climbing. On the other hand, it should have the turbofan feature such as lower SFC to realize subsonic cruise and long-range reconnaissance. Traditional engine types, such as turbofan and turbojet, can't address all of these design objectives. Therefore, some innovative engine types has been presented and studied, such as combined cycle engine [2–5] and variable cycle engine [6–10].

As a new type of variable cycle engine (VCE), the ACE can change the air-flow and pressure ratio of fan and core-engine respectively, to adjust the cycle in wider range and reach various strict mission-requirements [11]. There are several configurations of ACE, such as the ACE with Flade-fan stage, the ACE with variable low pressure compression system, and the three-stream ACE [12–15]. The object of this study is the ACE with Flade-fan stage, whose configuration is shown in Fig. 1 [8]. It consists of a typical double bypass VCE, like YF120, and a third bypass duct surrounding the VCE. The concept of ACE was first put forward by GE and Allison in 2004 as the engine for supersonic transport. It is an important part of the VAATE program of the Unite States and has drawn universal attention due to its task adaptability [16].

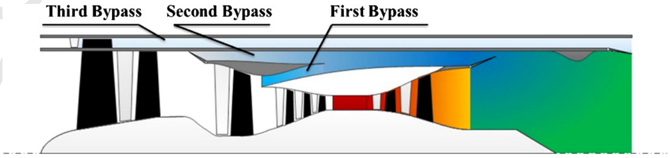

Fig. 1. The configuration of an adaptive cycle engine.

In order to achieve the design objectives, many variable-geometries with new technology characteristic are introduced to ACE. Ideally, engine component performance is absolutely consistent with the design value. However, the deviation arising from manufacture, assembly, and the deterioration during service can make component performance uncertain, which affects the engine overall performance. Sometimes these uncertainties make the engine overall performance, such as thrust and specific fuel consumption (SFC), deteriorate and even fail to meet the mission requirement [17–23]. Among those component performance uncertainties, the uncertainties in rotating component flow capac-

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ity and efficiency have main effect on engine overall performance [24–28]. Considering the effect of uncertainty in component performance, deviation standard is introduced during the traditional deterministic design process, which is based on the hard-won experience [29–32]. Due to the new technology applied to ACE and the complex matching mechanisms between the components of ACE, former experience may be unreliable, which may make the standard too strict or too loose. If the standard is set too strict, the manufacture cost seems to be unaffordable. What's more, the standard is limited by the design and manufacture technology. If the standard is set too loose, the ACE performance may not reach the mission requirement. Therefore, uncertainty quantification method should be introduced to obtain proper standard of CPD and make ACE reach the mission requirement.

There are three main approaches to quantifying the effects of uncertainties: probabilistic method, fuzzy sets method and interval analysis. Probabilistic method is based on defined probability density functions of the uncertainties. It is always developed by Monte Carlo simulation method and other random experiment methods. This method is mainly applied to the reliability design of both component performance and engine overall performance [33–36]. Fuzzy sets method is based on defined membership function of the uncertainties. This method is derived from fuzzy mathematics and is mainly applied to gas turbine fault diagnosis [37–40]. Both probability density function and membership function are defined based on large amounts of statistical data, which is difficult to obtain during the concept design of ACE. In contrast to another two methods, interval analysis is applied to solve the problem with uncertain-but-bounded parameters. Considering the boundaries of component performance are much easier to obtain than their probability density functions and membership functions, interval analysis is implemented in this paper to investigate the effects of the uncertainty in component performance.

As a non-probabilistic approach, interval analysis is mainly applied to the static analysis of structures. The exact response of the system with uncertain-but-bounded parameters can be derived through the vertex method [41,42]. This method considers all possible combinations of the parameters' interval bounds. The exact interval of response can be obtained by the maximum and minimum of the results. However, computational effort increases exponentially with the number of input uncertain parameters. Rao et al. presented a method based on and Gaussian elimination techniques and an inequality-based method to investigate the modeling of uncertain structural systems. This method can reduce the computational cost, but the intervals of solution vectors become wider than the true widths with the increase of the size of the problem [43]. For the system with large number of uncertain parameters, the interval perturbation method is a feasible solution. Qiu et al. presented the method based on first-order perturbation approach to analysis the static responses of structures with uncertain parameters [44,45]. However, this method neglects the interactions between the parameters, which will affect the accuracy of the result. S. McWilliam improved this method by taking some account of the interactions between the parameters in the stiffness matrix and force vector [46]. Qiu et al. also improved this method by taking advantage of interval mathematics in 2005 [47]. N. Impollonia et al. presented an interval analysis method based on approximate interval-valued Sherman–Morrison–Woodbury to analyze the linear structures with interval axial stiffness under static known loads in 2011. Numerical results verified the accuracy and the effectiveness of this method [48]. All of these methods mentioned above are based on the explicit function relationship between the uncertain-but-bounded parameters and the system response. For the gas turbine engine, there is no explicit function relationship between the component performance and engine overall performance, which makes it difficult for the application of these interval analysis methods.

The aim of this investigation is to obtain proper standard of CPD that makes ACE reach mission requirement. For normal interval analysis problem, the intervals of uncertainties are given, and the interval of system response is unknown. The interval of system response can be derived through certain interval analysis methods. In this study, the uncertainties are the CPD, which are unknown. The system response is the ACE overall performance, whose variation interval is determined by the mission requirement. Therefore, searching standard of CPD is an inversion process of the normal interval analysis. For the method with complex structure, the corresponding inversion process is always complex and difficult to achieve. For the method with simple structure, the result is always not accurate enough. Dealing with the contradiction between the simplicity and accuracy of the interval analysis method is one challenge for this study. What's more, the method should take the impact of CPD into consideration to obtain the proper deviation standard. On the one hand, the deviation of different component parameters may have different impact on overall performance. On the other hand, the deviation standard is limited by the technology and has a positive correlation with the manufacture cost. Therefore, it's wasteful and even impractical to set strict and uniform standard for all of the CPD. A reasonable solution is setting the deviation standard according to the impact of CPD, which is another challenge for this study.

A method based on first order Taylor series expansion is put forward to set the standard of CPD. Due to the simple structure of first order Taylor series expansion, it's convenient to estimate the intervals of CPD at given ACE overall performance deviation intervals without large amounts of calculation. What's more, the deviation standard obtained by this method can take the impact of CPD into consideration. Considering the interval analysis based on first order Taylor series expansion is not precise enough, error of estimation is introduced into the correction iteration. Finally, the standard of CPD can be obtained accurately and efficiently. Two operating modes are investigated in this paper. For each operating mode, two operating points are taken into consideration.

In this paper, 'Introduction' section introduces the necessity of setting standard of CPD by interval analysis and the challenge during this process. The following section presents ACE structure analysis and performance model applied in this paper. Section 3 discusses the difference between effects of CPD through sensitivity analysis and explains the result by the matching mechanism analysis of ACE. Section 4 estimates proper standard of CPD by interval analysis based on first order Taylor series expansion. Numerical simulation is used to evidence the feasibility and the effectiveness of this method. Final section draws the conclusions.

2. Introduction of ACE structure and performance model

2.1. Structure analysis

The main components of ACE are shown in Fig. 2. There is a row of variable stator vane in the inlet of third bypass. The blade of main fan extends into third bypass as a single compression stage. The blade in the third bypass and variable stator vane are defined as one component named FLADE. The fan system of ACE is divided into two sections, including main fan stage (FAN) and core driven fan stage (CDFS). Main fan stage is driven by low pressure turbine (LPT), while CDFS and high pressure compressor (HPC) are driven by high pressure turbine (HPT) [49].

There are several variable geometries introduced to ACE, which can be divided into two groups: one has variable stator vane, including FLADE, CDFS, and HPC. The other has variable area nozzle, including HPT, LPT, Front variable area bypass injector (Front-VABI),

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