Application of Sub-Model Technology in Reliability Analysis of Aero-Engine Turbine Disks

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Abstract: Aero-engine turbine disks are subjected to high-speed centrifugal loads, non-uniform temperature fields, and start-stop cycles. High stress gradients and localized plasticity easily form in the tenon, hole edges, and hub transition areas. Full-disk fine-scale finite element analysis (FEM) is costly due to contact nonlinearity and probabilistic sampling. Finite element sub-models, on the other hand, achieve scale separation through a process of "global solution-local truncation-boundary field interpolation-fine-scale solution." This paper reviews the basic principles, local modeling objects of turbine disks, reliability coupling process, typical failure modes, and methodological differences. Research shows that sub-models can reduce the cost of local analysis, but their reliability depends on the cut boundaries, global model accuracy, field variable transfer, and local nonlinearity handling. Future development should focus on multi-field bidirectional coupling, adaptive error control, fusion of manufacturing and measured data, and intelligent physical information models oriented towards multiple failure modes.

Keywords: Aero-Engine; Turbine Disk; Finite Element Sub-Model; Fatigue Reliability; Uncertainty Quantification

1. Introduction

Turbine disks are high-energy rotating life-limiting components in aero-engines, and their failure can lead to non-containment damage. Centrifugal force, thermal gradient, blade load, and assembly contact work together to concentrate the hazardous response in a small, complex region. If the entire disk is uniformly meshed with extremely fine meshes, the repetitive solutions in Monte Carlo sampling, sensitivity analysis, and reliability optimization will impose a huge computational burden.

The sub-model technique is based on Saint-Venant's principle. It refines the target region while maintaining the load path and constraints of the whole disk and transmits global field variables such as displacement and temperature. Cormier et al. demonstrated its advantages and applicable conditions in handling stress concentration earlier [1]. The "sub-model" referred to in this paper specifically refers to the finite element global-local technique, rather than the proxy model, and focuses on discussing the shortcomings of local response reliability, probabilistic reliability coupling and multi-field multi-failure mode.

2. Literature Sources and Screening Guidelines

This study searched Web of Science Core Collection, Scopus, ScienceDirect, SpringerLink, ASME Digital Collection, CNKI, and DOAJ, covering the period from January 1998 to July 2026. Chinese keywords included "turbine disk," "submodel," "global-local finite element," "tenon-groove contact," "fatigue reliability," and "crack propagation." English keywords included "turbine disk/disc," "finite element submodeling," "global-local model," "dovetail/fir-tree attachment," "fatigue reliability," and "probabilistic life." Research in peer-reviewed journals directly related to aero-engines or similar disk-like structures, with complete methods and results supporting arguments for the accuracy or probabilistic reliability of the submodel, was included. Results only involving blade aerodynamics, lacking local modeling, duplicate publications, or incomplete information were excluded. Finally, 20 representative articles were selected.

3. Main Overview

3.1 Sub-Model Technology Principles and Credibility Control

The sub-model first obtains the displacement and temperature fields from the whole disk or cyclic symmetric sector model, then selects the critical area, interpolates the global results to the cutting boundary, and uses fine mesh, high-order elements, and contact, plastic, or crack models. The assumption is that local refinement does not significantly change the far-field load path; therefore, the boundary should be far from the hole edge, contact edge, material abrupt change, and plastic zone. As shown in Figure 1, the turbine disk global model first calculates the overall response under the combined action of centrifugal load, temperature field, and blade load, and selects stress concentration areas such as tenons and grooves to establish local sub-models. The displacement and temperature fields of the global model are interpolated to the cutting boundary of the sub-model. Through local mesh refinement and contact and plastic nonlinear modeling, a high-precision stress - strain response in the critical area is obtained.

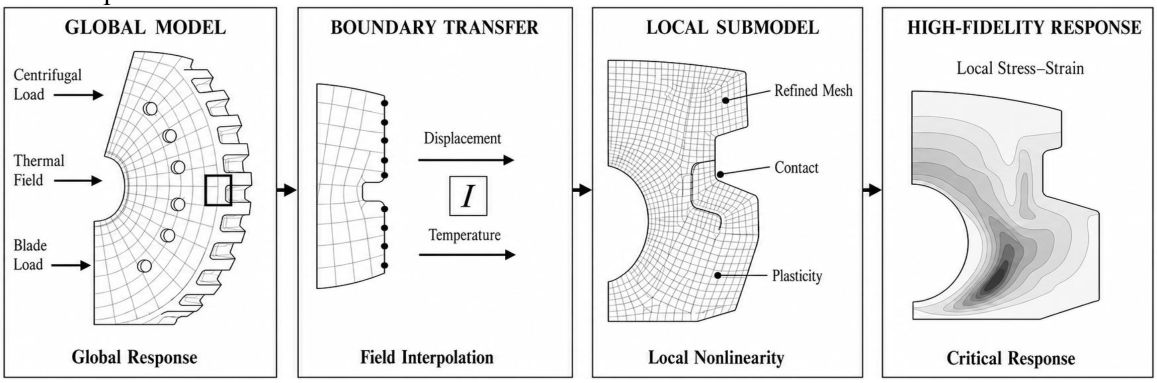

Figure 1. Principle of Global-Local Finite Element Sub-Model Technology for Turbine Disks

Errors come from global discretization, boundary interpolation and local discretization. Kardak and Sinclair pointed out that verification should not only compare peak values, but also carry out global mesh convergence, boundary outward movement and local refinement, and examine stress path stability [2]. Thermal-structural coupling also requires that coordinates, units, time steps and material parameters be consistent; if local contact significantly feeds back the overall stiffness, iterative global-local coupling is required.

3.2 Evolution of Turbine Disk Local Modeling Objects and Applications

Early studies focused on the blade-disc connection area. Papanikos et al. revealed the influence of dovetail connection geometry, contact and friction on local stress[3]; Meguid et al. compared the two-dimensional and three-dimensional responses of fir tree tenons, indicating that the groove and thickness effects need to be described by a local three-dimensional model[4]. The path of far-field constraints provided by the whole disk or sector and the local model capturing the high gradient of the contact is thus formed.

Subsequent research shifted to contact stress convergence. Sinclair et al. showed that the contact edge element scale must be sufficiently small relative to the local radius of curvature [5]. Beisheim and Sinclair improved the three-dimensional boundary transfer by fitting displacement surfaces [6], and used a continuous two-level sub-model to handle friction and crown edge trimming, proving that multi-level refinement is suitable for extremely steep gradients [7]. The application was then extended to vents, bolt holes, grates and hub transition areas. Yan et al. combined variable-size sub-models with automatic meshing and genetic algorithms for vent shape optimization [8].

3.3 Coupling Mechanism Between Sub-Model and Reliability Analysis

Deterministic sub-models output local stress, strain, or fracture parameters, while reliability analysis must also consider stochastic factors such as rotational speed, temperature, blade mass, material strength, geometric tolerances, and initial defects. A typical process involves establishing random variables and related structures, obtaining boundary responses through a global model, driving sub-models, constructing the limit state function g(X), and then estimating the failure probability using sampling methods, reliability index methods, or surrogate models. As shown in Figure 2, the global model first calculates the overall thermo - mechanical response of the turbine disk under rotational speed, temperature, and blade loads , and then transfers boundary fields such as displacement and temperature to the refined sub-model in the critical region. The sub-model obtains the local stress - strain responses at locations such as tongues and grooves and hole edges , then incorporates material, load, and geometric uncertainties into the limit state function, ultimately calculating the failure probability and reliability.

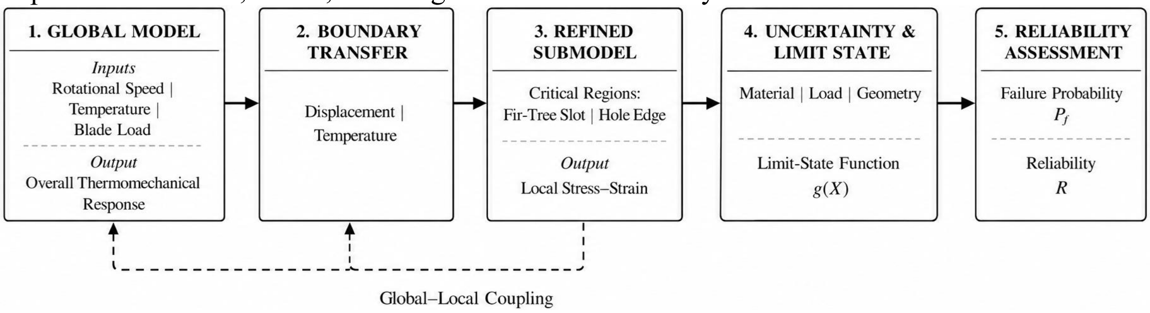

Figure 2. Coupling Mechanism between Sub-Modeling Technology and Turbine Disk Reliability Analysis

Melis et al. used Weibull statistics to link disk life and reliability, demonstrating the necessity of probabilistic life analysis [9]. Zhu et al. established a Bayesian low-cycle fatigue framework that can update parameter distributions from experimental data [10], and then used failure physics to uniformly transmit randomness and cognitive uncertainty [11]. Their computational-experimental fusion study combined stochastic finite element analysis, full-scale overrunning tests, and sensitivity analysis, which improved the verifiability of risk assessment [12]. Niu et al. further explained that reliability is also affected by distribution form, correlation, and model error [13].

The sub-model provides the local physical response for the limit state function. Solving the global and local models repeatedly for each sample yields high accuracy but is costly; when the global response is approximately linear, boundary mappings can be pre-built, and only the local model needs to be solved repeatedly; for large samples, surrogate models such as Kriging can be used to approximate the "random input-local response". The sub-model is responsible for spatial localization, while the surrogate model is responsible for sample acceleration; the two can be cascaded.

3.4 Typical Failure Modes and Application Scenarios

The first type of application is low-cycle fatigue of tongue and groove and disc rim. The sub-model refines the contact surface, fillets and groove bottom, and provides elastoplastic strain to Manson-Coffin, SWT or energy-type models. Witek found that the actual disc crack origin coincides with the high-stress area of the lower fir groove, indicating that local response can support failure localization[14].

The second category is high-temperature fatigue-creep, which requires the introduction of temperature-related parameters, cyclic plasticity, and load-holding creep. Tomevenya and Liu's evaluation of the GH4133 disk shows that the dispersion of temperature, material, and load significantly changes the reliability [15]. The third category is crack initiation and propagation, which can embed defects and calculate stress intensity factor, J integral, or propagation life. The fourth category is fuzzy failure boundary. Huang Xiaoyu et al. used active learning Kriging to solve the fuzzy fatigue failure probability, indicating that the damage threshold may not be suitable for an absolute binary description [16].

3.5 Method Comparison and Evaluation

The full-scale model has a complete load path, which is suitable for benchmark verification, but it has the highest cost in contact, crack and probability sampling; the cyclic symmetric model is efficient, but it is difficult to cover non-periodic defects, circumferential temperature difference and detuning. Single-level sub-models are suitable for far-field unidirectional drive, while multi-level or iterative sub-models are suitable for strong gradient and stiffness feedback, but the convergence control is more complicated. Song et al.'s distributed cooperative wavelet neural network improved the efficiency of low probability cyclic fatigue assessment [17]; Yao et al. used active learning Kriging to identify the failure boundary of double-spoke plate disks[18]. However, the surrogate error will be superimposed with the sub-model boundary error, and the small failure probability area still needs to be verified.

Sub-models are best suited for problems where "the overall load determines the far field and the local geometry determines the failure." Their advantages include high local accuracy and ease of introducing cracks or nonlinearities. However, their disadvantages include reliance on experience for boundary selection and unidirectional transmission that ignores feedback. In engineering practice, the global model should be calibrated using whole-disk or experimental methods, while the local model should be verified through dual convergence of mesh and boundary parameters. Then, direct sampling or surrogate acceleration should be selected based on the sample size.

4. Current Research Deficiencies and Development Trends

4.1 current Research is Insufficient

Existing research suffers from error chain fragmentation, with most studies validating global, sub-models, or surrogate models separately, lacking a unified error budget encompassing "global discretization-boundary interpolation-local discretization-lifetime model-probabilistic estimation." Loads and materials are often simplified as independent steady-state variables, insufficiently considering mission spectra, time-varying temperatures, rotational speed-temperature correlations, and the spatial discretization of batch materials. Local models often focus on single critical points and failure modes, rarely systematically addressing related failures at the disk center, disk rim, tenon grooves, and hole edges; residual stress, surface integrity, micro-defects, and service damage data are also insufficiently incorporated. Publicly available research remains primarily based on numerical examples or single-piece tests, lacking cross-batch, cross-condition, and full-lifetime validation.

4.2 Development Trend

Future research will shift towards transient thermo-mechanical-contact multi-field bidirectional coupling, and adaptively adjust boundaries and meshes based on energy norm, stress path, and failure probability contributions. Manufacturing, non-destructive testing, materials testing, and flight load data can be incorporated into the model through Bayesian updates, transforming reliability assessment from a design-prior basis to a dynamic service evaluation. For multi-hazard areas, a group of correlated sub-models sharing a global boundary should be established to handle failure correlations for system reliability.

Physical information intelligent models are another direction. Li et al. embedded the physical mapping of materials and components into ensemble learning for the fatigue reliability analysis of bladed disks [19]; Song et al. constructed a multi-output XGBoost model of disk center and disk edge, showing that intelligent methods are expanding from single-point life prediction to multi-objective risk assessment [20]. The focus of the next step is to preserve the conservation relationship, contact constraints and life monotonicity, and to give an auditable uncertainty limit for the minimum failure probability interval.

5. Conclusion

The finite element sub-model, by separating the overall response of the entire disk from the response of local hazardous areas, balances accuracy and efficiency in turbine disk reliability analysis. Research has expanded from tenon-groove contact stress to low-cycle fatigue, fatigue-creep, crack propagation, fuzzy failure, and assessment of multiple hazardous locations. Reliable applications rely on correct global load paths, cutting boundaries far from strongly nonlinear regions, convergent verification of the mesh and boundaries, and joint quantification of model and probability errors. Future research should advance multi-field bidirectional coupling, measured data updates, and intelligent acceleration of multi-sub-model system reliability and physical information, enabling the sub-model to evolve into a verifiable and updatable full-lifecycle reliability analysis platform.

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