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Abstract

HCF of turbomachinery blading is a significant design problem because fatigue failures can result from resonant vibratory stresses sustained over a relatively short time. Fatigue failure result from a combination of steady stress, vibratory stress, and material imperfections. However, the size of microscopic imperfections is difficult to control. Hence, stress-range diagrams are used to quantify the allowable vibratory stress amplitudes to avoid fatigue damage. Advanced turbomachinery blading is designed to have high steady stress levels. Thus, HCF occurs because of high mean stress - low amplitude vibratory loading of the airfoils. The prediction of the vibratory stress level for input to the stress-range diagram requires the analysis of the blade row unsteady aerodynamics, structural characteristics, and resonant vibration response. This is because the root cause of the vibratory stress is flow-induced vibrations.

Introduction

High cycle fatigue (HCF) resulting in the loss of gas turbine engine blades or disks is currently the predominant surprise engine failure mode after the completion of engine development. This is a direct result of the introduction of high thrust-to-weight ratio engines, accomplished by increasing the mass flow and utilizing fewer parts. The required compressor designs featured fewer stages comprised of closely spaced rows of thin low aspect ratio balding with high tip speeds. The increased mass flow then results in a significant increase in the aerodynamic loading and the steady state stress. Also, the mechanical damping is considerably reduced in newer rotor designs. As a result, the low aspect ratio balding of advanced high thrust-to-weight ratio engines have experienced unexpected reliability issues, with HCF of particular concern.

HCF is metal fatigue that results from cracking or fracture phenomenon generally characterized by the failure of small cracks at stress levels substantially lower than stresses associated with steady loading. Namely, HCF results from a combination of steady stress, vibratory stress, and material imperfections. It is initiated by the formation of a small, often microscopic, crack. The vibratory stress levels required to produce a fatigue crack at a specific mean stress level are then determined from stress-range diagrams, Figure 1.

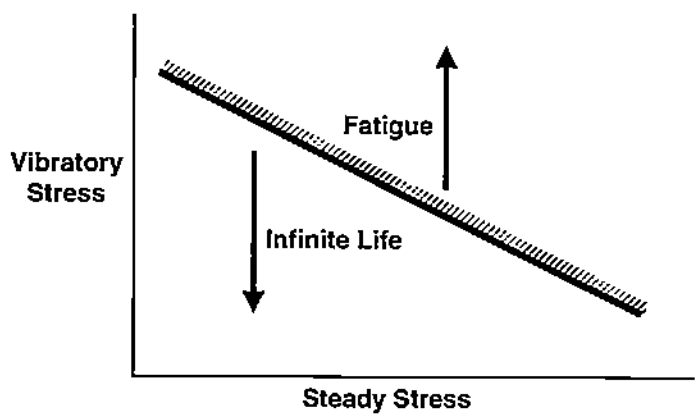

Figure 1. Schematic stress-range diagram

Advanced turbomachinery blading is designed to have high steady stress levels. Thus, HCF occurs because of high mean stress - low amplitude vibratory loading of the airfoils, Figure 2.

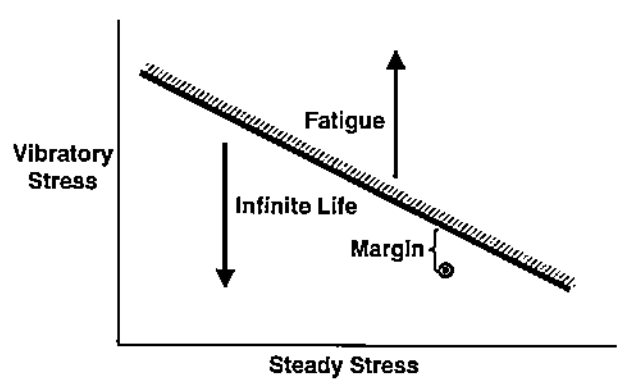

Figure 2. Advanced airfoil stress-range diagram

The technical challenge is to predict the vibratory stress for each airfoil row.

Vibratory Stress Prediction

The prediction of the vibratory stress level for input to the stress-range diagram requires the analysis of the blade row unsteady aerodynamics, structural characteristics, and resonant vibration response. This is because the root cause of the vibratory stress is flow-induced vibrations. Namely, integral order forced vibrations can occur in fan, compressor, and turbine blading when a periodic aerodynamic forcing function, with frequency near a system resonant frequency acts on a given blade row. These forcing functions are generated at multiples of the engine rotational frequency and arise from a variety of sources both internal and external to the engine.

The rotor speeds at which significant forced vibrations may occur are predicted with frequency-speed or Campbell diagrams, Figure 3.

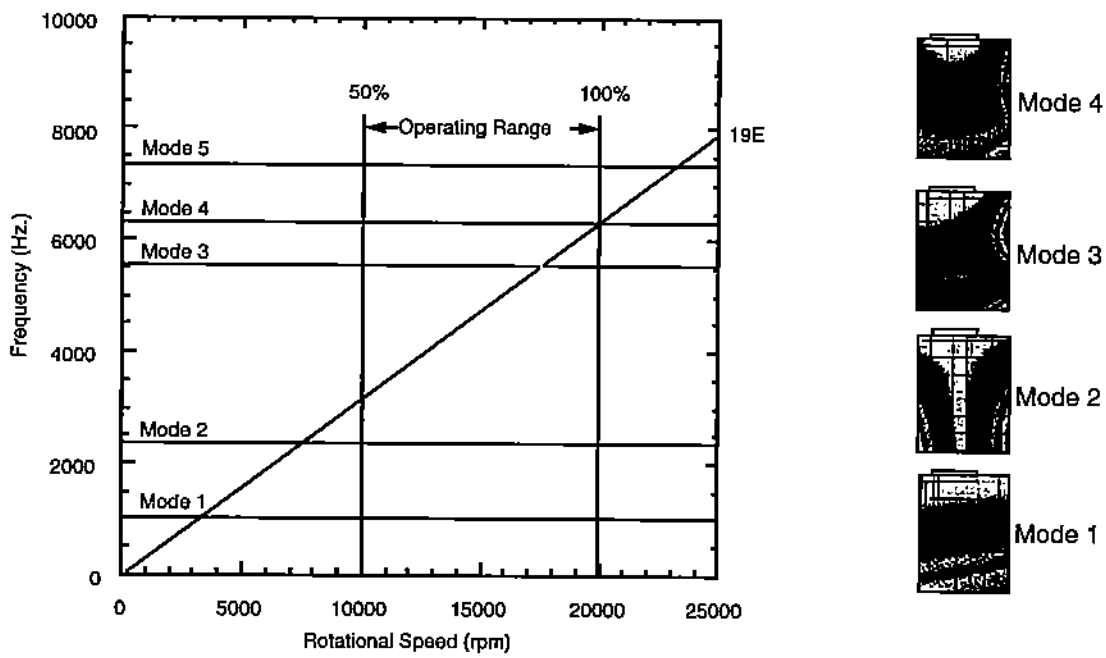

Figure 3. Campbell diagram

These display the natural frequency of each blade vibration mode and the forcing function frequencies as functions of rotor speed. The intersections of these curves indicate the integral order resonance points at which the possibility of high vibratory stresses exist. It is not always possible to eliminate the sources of forced vibration from the operating range of a turbomachine. Because a blade may have as many critical points of high stress as it has natural modes, the designer must determine which particular modes have the greatest potential for aerodynamic excitation. This requires the prediction of the resonant aerodynamically forced vibration response and vibratory stress of the airfoil row at each intersection point on the Campbell diagram.

To predict blade life or design blades for longer HCF life, accurate predictions of the blade vibratory stress are crucial. A detailed schematic of the vibratory stress prediction system for turbomachinery blading is depicted in Figure 4.

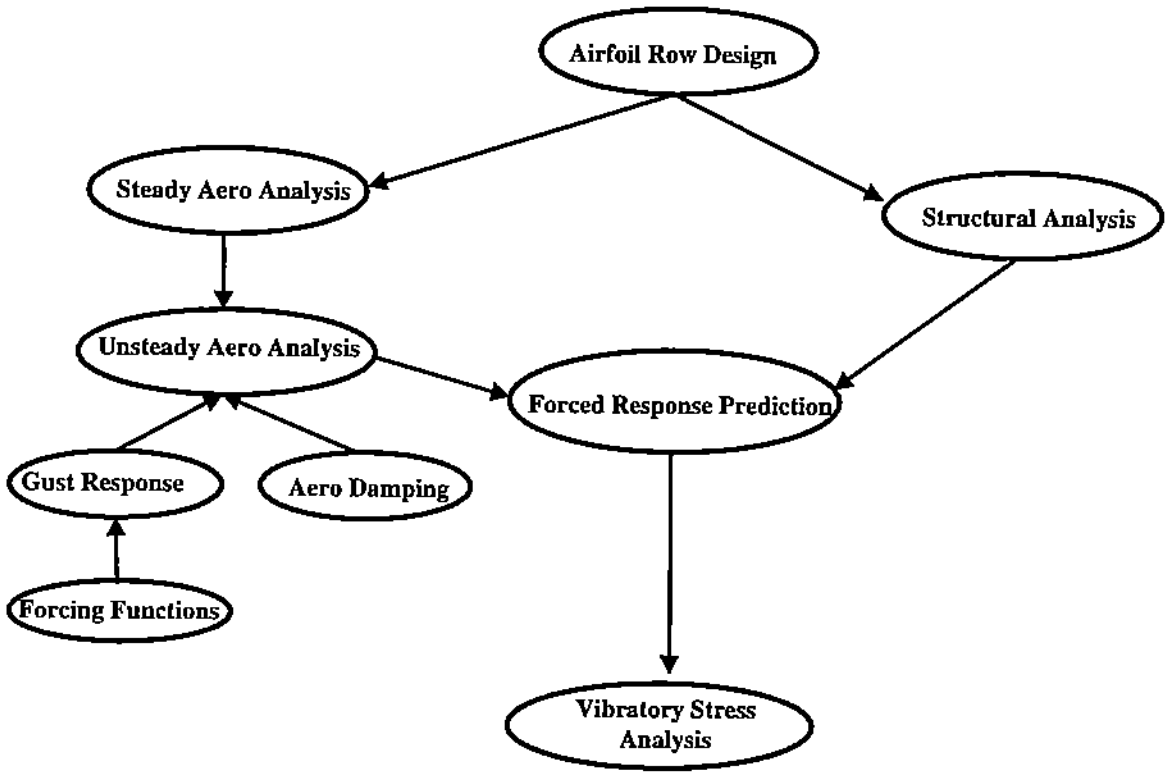

Figure 4. Blade vibratory stress prediction schematic

First the airfoil row is designed to achieve its steady performance requirements. Based on this design, the blade natural frequencies and mode shapes are analyzed by means of a finite element structural analysis, with the detailed blade row steady aerodynamics predicted utilizing a computational fluid dynamic (CFD) model.

The blade row unsteady aerodynamics are then predicted utilizing CFD analysis to predict the aerodynamic damping together with the aerodynamic forcing functions and the resulting gust response. Current design system unsteady aerodynamic analyses generally consider the response of an isolated blade row, with both linear frequency domain and nonlinear time-marching analyses utilized. Both approaches require the specification of the unsteady aerodynamic forcing function and the vibration mode shape. Thus, there are two separate systems of equations to be solved – the structural system and the fluid system. They are coupled only in that the aerodynamic forces and blade state are passed between each other after each time step.

The most common unsteady aerodynamic forcing functions are wakes generated by an upstream airfoil row. For example, consider the single stage geometry shown in Figure 5 in which the rotor wakes are the unsteady aerodynamic forcing function to the downstream stator vane row. A reduction in the relative velocity in the wake causes a decrease in the absolute velocity as well as an incidence increase to the downstream stator vanes. This produces fluctuating forces on the downstream airfoils.

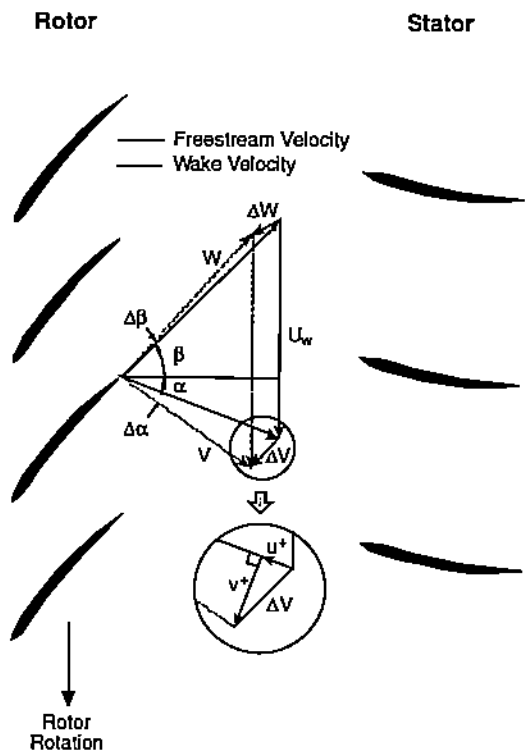

Figure 5. Rotor generated wake-forcing function

The structural characteristics of the blading, including the mode shape and natural frequencies, are predicted with finite element analyses. The structural analysis is then coupled with the unsteady aerodynamic analysis through an aeroelastic forced response analysis that predicts the airfoil vibration response. A separate analysis is then required to determine the resulting vibratory stress. The potential for HCF failure is then predicted by determining the effect of the combined mean and cyclic stress, accomplished with stress-life (S-N) diagrams which are concerned with component life to failure.

It should be noted that even though sufficient fatigue margin is provided for the design airfoil, manufacturing results in a distribution of airfoil properties. This results in a statistical variation of the vibratory stress, with the possibility of a HCF failure of one airfoil in the row, as schematically depicted in Figure 6.

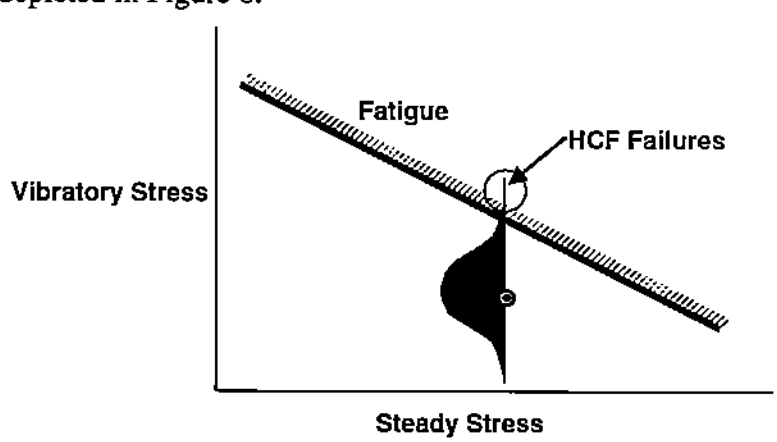

Figure 6. Statistical stress-range diagram schematic

In summary, HCF of turbomachinery blading is a significant design problem because fatigue failures can result from resonant vibratory stresses sustained over a relatively short time. Blade and thus engine durability and life are dependent on the vibratory stress level for a given steady operating stress. To avoid costly and time consuming development problems and to maximize engine life and time between overhauls, it is necessary to accurately predict the level of vibratory stress. This requires the analysis of both the structural mechanics and the unsteady aerodynamics of bladed disks to predict the vibratory stress level, with a stress range diagrams utilized to predict the maximum vibratory stress for infinite life.

PROBLEM

Current unsteady aerodynamic CFD models typically consider a single blade row. Thus, a number of surprise HCF failures may be a result of inadequate modeling of multistage effects. Turbomachinery performance aerodynamicists have found that the mean (steady) flow through a turbomachine can be modeled quite accurately by examining each blade row in isolation. However, multistage unsteady flow analyses have shown that multistage effects can indeed be quite significant, with the aeromechanics of isolated blade rows much different than that of blade rows in a multistage environment. Put bluntly, the isolated blade row analyses that have been extensively developed over the past several decades may be lack the essential physics modeling to predict accurately high cycle fatigue.

Another limitation of current HCF predictions is that they predict the blade row unsteady aerodynamics for a specified blade motion, for example bending or torsion. Thus, there are two separate systems of equations to be solved – the structural system and the fluid system. They are coupled only in that the aerodynamic forces and blade state are passed between each other after each time step. This pseudo-coupling approach produces phase-lagging errors that can act as energy sources or sinks in the system.

Fluid-structure interaction that more precisely models the energy exchange between the fluid and structure is obtained by modeling both the fluid and structure with consistent numerical schemes, i.e., a truly coupled structure interaction model for turbomachine blade rows appropriate for all flow regimes with no phase-lagging errors. The resulting fluid-structure interaction blade vibratory stress and HCF life prediction schematic is shown in Figure 7.

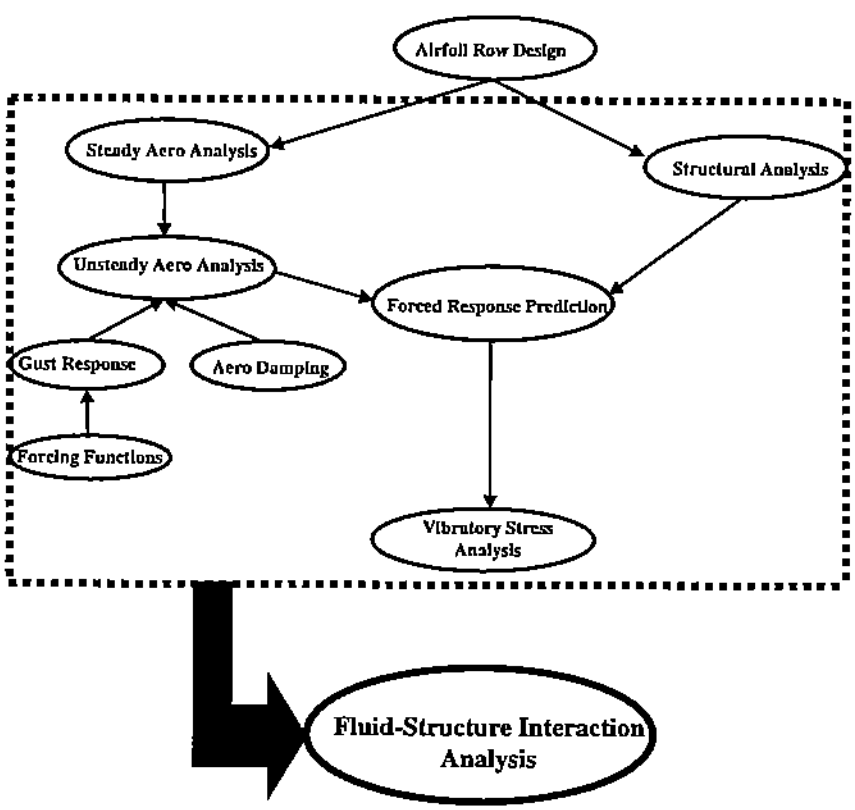

Figure 7. Fluid-structure interaction blade vibratory stress and HCF life prediction

This research begins to address this need. Namely, a finite element model able to handle both fluid and solids has been developed at Lawrence Livermore National Laboratories. This code, Arbitrary Lagrangian-Eulerian/3D (ALE3D), was developed from the DYNA3D model [1] with the added capability to handle general fluid-structure interaction problems, especially those involving plastic deformations. Phenomena can be modeled from the Lagrangian or Eulerian perspectives, or from any arbitrary reference frame. This approach is well suited for fluid-structure interaction problems where the structure is best modeled from the Lagrangian perspective, while the fluid is typically modeled from the Eulerian point of view. Since the same finite element method is used for the fluid and the structure, dynamic consistency is assured.

Unfortunate ALE3D cannot be directly applied to fluid-structure interaction problems in the turbomachinery environment. Modifications are necessary to include appropriate turbomachine blade and flow mesh algorithms. In particular, periodic boundary conditions must be added to the sides of the domain so that only one blade passage needs to be analyzed. The hub and tip of the flow passage must be modified so that there is no fluid acceleration or velocity normal to these surfaces. The inflow boundary must be modified to allow for variable inflow velocity. Appropriate routines to output blade surface pressures at various sections, mass flow rate, and other mass averaged properties are also necessary additions to the code. The resulting Turbomachinery AeroMechanics code is called TAM-ALE3D, with its ability to model unsteady turbomachinery aerodynamics validated [2].

Acknowledgement

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