FRETTING FATIGUE INVESTIGATION OF DOVETAIL

Sam Naboulsi[1] and Jeff Calcaterra[2]

[1]Department of Aeronautics and Astronautics
Air Force Institute of Technology (AFIT/ENY)
[2]Air Force Research Laboratory
Materials and Manufacturing Directorate (AFRL/MLLMN)

ABSTRACT

Turbine engine jet exhibits superior output power-to-weight ratio, which has made it the mainstay of modern aviation propulsion for both civilian and military application. Life prediction methodologies of turbine engine's material under typical operating conditions are one of the main priorities for the USAF, since it is one of the most significant drivers of structural integrity damage and catastrophic failure. An extensive effort to understand structure-property relationships that govern the useful life of two titanium bodies, i.e. blade and disk in turbine engine, under fretting fatigue is ongoing as part of the Air Force structural integrity program. This study extends relationships governing fretting fatigue developed under controlled laboratory conditions into a real blade-disk application under realistic operation conditions. Fretting fatigue is complex phenomena. It depends on geometry and loading conditions, which are essential to the analyses of an actual blade-disk in a turbine engine jet. Thus, aeroelastic analyses of blade will be performed. A special design tool for an actual dovetail slot of a single turbine engine blade is developed using an efficient hybrid technique that utilizes a combination of different numerical techniques to predict the contact stresses at the dovetail. Introducing such hybrid technique is dictated by the numerically extensive and the computationally expensive nature of modeling a full single blade using finite element. Such model requires a very refined mesh with an element size of micron or less to capture the state of very high intensity contact stresses at the dovetail. Hence, the present work uses a technique to couple a coarse finite element model with the semi-analytical contact model based on Singular Integral Equations (SIE) to compute the contact stresses along the full width of the dovetail.

1-INTRODUCTION

Significant numbers of failure in turbine engine components are attributed to fretting fatigue-related damage (see Figure 1a). Examples of these are routinely seen damage in dovetail joints of turbine engine blades including their press-fit or interlocking connections to the disk, which are subjected to surface wear and fretting fatigue. Currently, there are many research efforts to understand damage, crack initiation, and crack propagation under fretting fatigue [1-5]. They address key crack initiation and propagation mechanism and include relevant aspect of macrostructure, microstructure, surface characteristics and local contact stress field. Most of these studies are performed in laboratory environments where semi-ideal conditions of fretting fatigue are imposed. They, in general, considered simplified geometry and loading conditions. However, fretting fatigue is geometry and loading conditions dependent, and it is essential to model an actual geometry of a blade-disk in a turbine engine jet, not a simplified form, and transient loading, not static one. Since, the primary mechanism of blade fatigue is caused by vibrations at levels exceeding material endurance limit where an actual turbine engine blade exposed to complex loading, e.g. inertia and aerodynamic due to rotating blade motion and air flow, respectively. For example, to assure engine stability during operation, it is design with a surge margin (i.e. some distance from the surge line, where unstable flow initiates) such that it operate under steady performance. To properly model it, one should analyze a complete engine simulation providing the capability for flow fields through the various components interaction. The simulation of the actual physical processes should also include the effects of three-dimensional, unsteady, turbulent viscous reacting flows and their interaction with the engine structural components. Further, an actual engine performance differs

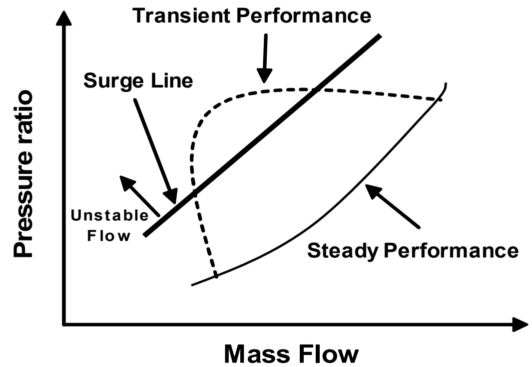


Figure-1a Bladed disk dovetail attachment region and its associated damage.

Figure -1b Schematic of engine performance.

from that design predicted steady flow performance. This is because of the inherent unsteady interactions that occur between the various components. Consequently, a dynamic transient performance results including unexpected crossing of surge line while transitioning between operation points (see Figure 1b). This unsteady engine operation produces extreme loading for the turbomachinery blades, resulting in high cycle fatigue (HCF) failure, where flow instabilities induce blade vibrations due to the rapid loading and unloading of the blades. To address these various issues associated with transient performance of a gas turbine engine, a complete engine simulation is required. Unfortunately, such model analysis requires vast computational resources.

Hence, a simplified model has been developed in the present study that primarily focuses on the simulation of fluid flow-structural interaction phenomena in an individual engine blade. A hybrid technique to investigate fretting fatigue in turbine engine components is developed where unsteady aerodynamic loading of an individual blade is included in the analyses using coupled fluid-structure interaction model. This technique combines an aero-elastic simulation with a slicing technique to computes the contact stress. The flow of the present paper is as follow. First, the slicing technique will be discussed. Second, the coupled fluid-structure interaction analysis of three-dimensional single blades will be presented. Third, the hybrid technique will be used to investigate two different blades and compare their predicted fretting fatigue life based on the computed contact stress.

2-HYBIRD TECHNIQUE

The present hybrid technique is a slicing technique, which combines an aero-elastic analysis and semi-analytical SIE method. The motivation behind the present hybrid technique is the draw backs of both the finite element and the semi-analytical SIE method. The former requires element refinement size of a micron or less near contact regions in order to capture the sharp stress gradients associated with fretting fatigue near the contact surface. Such fine mesh requires extensive computational time even for simple geometry such as cylindrical pad on finite substrate. For an actual geometry of a blade, as is the case in the present investigation, the complexity of creating a mesh as well as computational time of analyses even become extremely demanding/extensive if not computationally intolerable without sacrificing accuracy. The latter is a numerical solution to an analytical contact based formulation of stick-slip and stress/strain state associated with an indenter-substrate under fretting fatigue. It is based on assumptions of ideal conditions such as simple geometry, approximate supper-imposed bulk loading, infinite or half-plane substrate solutions, and elastic material properties. To overcome these disadvantages, limitations, and constraints, a hybrid technique combining the two methods numerically will be present. It is uncoupled technique, in the sense that the results from a coarse finite element model of an actual dovetail geometry used to compute the load at the contact zone at a given locations by slicing the mesh into finite number of segments. They are then feed into the semi-analytical SIE method at those specific locations where the actual dovetail geometry is sliced to reduce the geometry from a three-dimensional to a two-dimensional. It is an efficient technique used to obtain reasonably accurate results.

It should be pointed out that the following technical issues are addressed in this hybrid technique. First, only elastic constitutive laws are considered for the material in both the finite element and the SIE methods. Since, the vast majority of components stresses are elastic and the improved accuracy from addition of elastic-plastic analysis does not justify the increase in computational cost. Second, the interaction of third body particles is neglected and the effect of palliative coatings can be handled by changing the coefficient of friction. This can be achieved in the present hybrid technique by changing coefficient of friction during loading in the SIE analyses. Third, the SIE is a two dimensional method assuming a plane strain where quantities are defined per unit thickness out-of-plane. The SIE analysis at each slice is decoupled from the neighboring slices. This can be considered as a special case of submodeling, which does not enforcing continuity and produces an approximate solution. However, this technique is sufficient to produce a reasonably accuracy contact stresses efficiently.

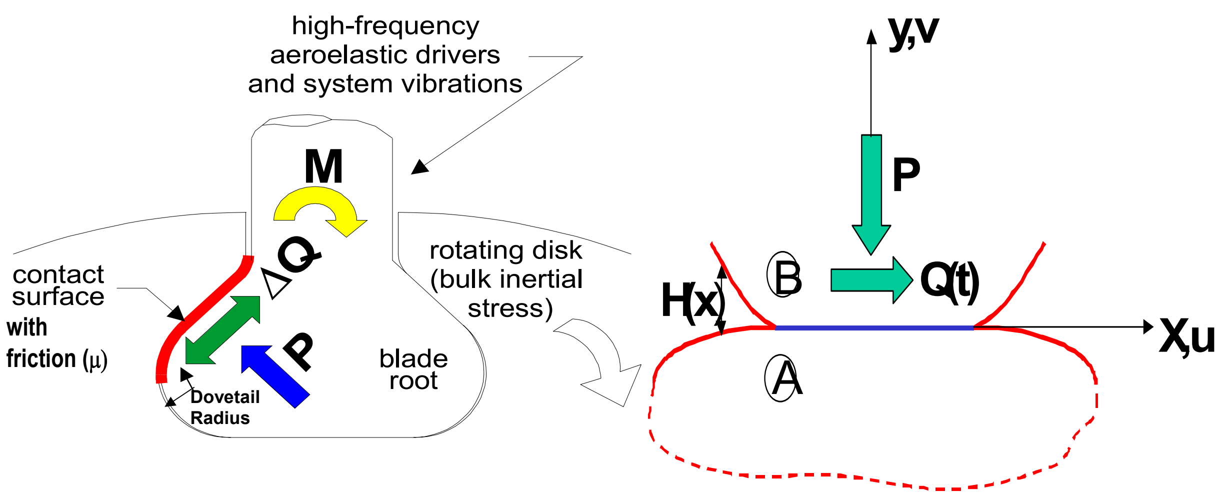


Figure-3 Schematic of the global forces acting on a typical dovetail joint and the fretting contact conditions represented in the SIE method.

2.1- SEMI_ANALYTICAL SIE MODELING

The theory of the SIE method is presented in Reference [6]. The SIE is a two dimensional method, which assumes a unit thickness out-of-plan. It simplifies the contact zone for a dovetail by considering an arbitrary profile (e.g. flat contact zone with rounded or cylindrical indenter, which are most appropriate for fretting fatigue of a dovetail) in contact with flat half-plan substrate as shown in Figure 3. The indenter's profile is defined by a function, which represents the gap between the indenter and the substrate as shown in Figure 3. The surface normal traction can be obtained from the surface profile, and the shear traction distribution at the surface can also be obtained for partial slip using CAPRI code [6].

2.2- Finite Element Modeling

The present investigation uses finite element to model unsteady engine operation. A fluid-structural interaction simulation performed in order to model extreme loading of turbo machinery. A single blade (i.e. without a disk attachment or multi-components disk-blade attachments) is model where nonlinear contact mechanics between the surfaces of the blade-disk attachment is replaced by fixed boundary condition. That is the contact surfaces at the dovetail joint of a turbine engine blade including their press-fit or interlocking connections assumed locked with no slip. It physically represents a scenario where the blade bearing against the disk at idle speed is high to enforce a bond/interlock between the blade and disk at high rotating speed. This is a conservative assumption. Even though the finite element analyses are contact mechanics free, the slicing technique integrates contact mechanics using the SIE method as discussed above.

The finite element analyses performed using the explicit code LS-DYNA. The code used to solve steady state or transient fluid flow about a body using boundary element method. It has the capability to model unsteady flow with arbitrary body motion, where such fluid-structure interaction is restricted to inviscid incompressible attached fluid flow (i.e. no shocks or cavitations can be modeled using the present approach). A subsonic flow with high Reynolds number and small effects of viscosity is assumed to apply for the present fluid-structure interaction of blades. The boundary condition is no flow in the direction normal to the surface of the body. The above equation is solved by discrediting the surface of the body with a set of quadrilateral or triangular boundary elements (see Figure 4). Three-dimensional finite element analyses of geometrically complex blades assuming elastic material response is performed. The fluid-structure interaction is modeled by adding quadratic or triangular boundary elements to include the fluid flow effects. Several simplifications were made, which neglect thermal effects, inertia loads, and vibratory loads.

Blade A Blade B

Figure-4 Finite element meshes of two different blades: blade A and blade B.

3- NUMERICAL RESULTS AND DISCUSSION

The hybrid method has been developed to overcome the limitation in both the finite element and SIE analyses encountered in complex geometry by combing them to produce an economic, efficient, and accurate fretting fatigue analysis tool. Further, the present technique is intended to be a practical technique to be utilized as a designing tool to improve or inspect blade under fretting fatigue conditions. A practical problem should address the fretting fatigue complex damage process, which depend on pad geometries, surface properties, material properties, and mechanical loading conditions. The present paper focuses specifically on the complex loading conditions of blades. Specifically, an actual turbine engine blade exposed to aero-elastic loading. In order to demonstrate the practical capabilities of the hybrid technique, a fretting fatigue investigation of two actual blades, i.e. Blades A and B in Figure 4, will be presented. It compares their predicted fretting fatigue life. The two turbine engine blades have different design. The present study assumes that both blades have the same material properties and aero-elastic loading conditions. It further assumes that the predicted lives depend only on the contact stresses. That is a blade with higher computed contact stresses has lower fretting fatigue damage tolerance or lower fretting life. Hence, the blades are investigated using the hybrid technique and the results are compared as follow.

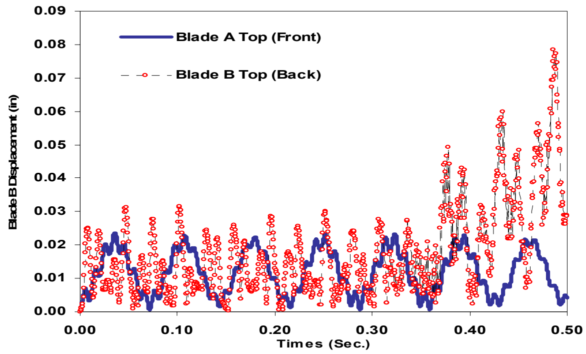


Figure-5 Comparison of the displacement for the two blades as a function of time.

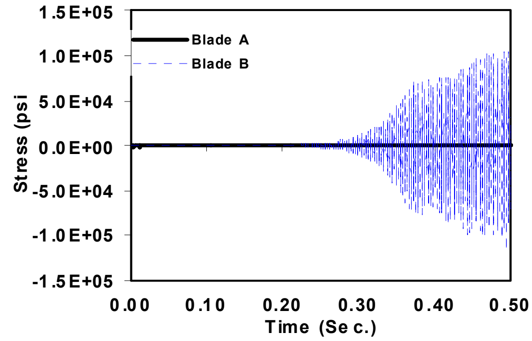


Figure-6 Comparison of the stress for the two blades as a function of time.

First, aero-elastic analysis of the blades is performed, and their displacement, stress, and forces as a function of time will be presented for comparison. The displacements of the tip of the two blades are shown in Figure 5. Comparing them, Figure 5 shows that blade A exhibits steady state cyclic deformation. However, blade B initially shows steady state deformation prior to an increase in its amplitude. Similarly, the hydrostatic stresses (i.e. pressure) are shown in Figure 6, and they show stable steady state cyclic pressure for blade A contrary to blade B. Also, the pressure of blade B is two order of magnitudes higher.

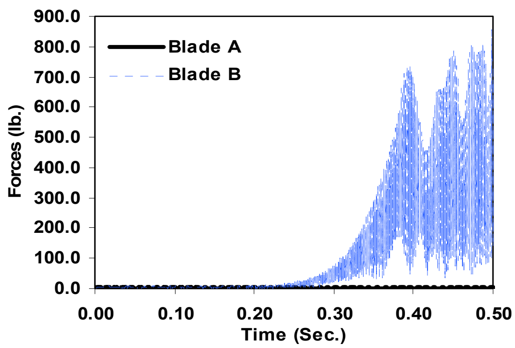


Figure-7 Comparison of tangential forces for the two blades as a function of time.

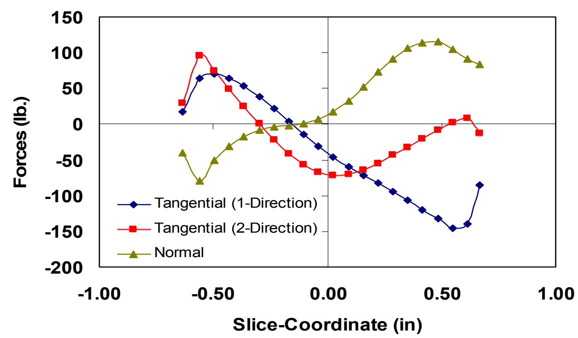


Figure-8 Comparison of the stress at a slice as a function of time.

.

The forces are also examined in details. They are the reaction forces in the analyses, since the blade-disk attachment surface (i.e. contact surface) is assumed fixed, which models full blade lock with no slips. Each blade has two contact surfaces, (i.e. right and left sides), and they are flat plan at some oblique angel in space. These forces are used as an input to the slice technique, which divides the contact surfaces into a number of segments and applies the two dimensional SIE to compute the contact stresses. Figure 7 shows tangential force for the two blades at a point on the contact surface as a function of time.

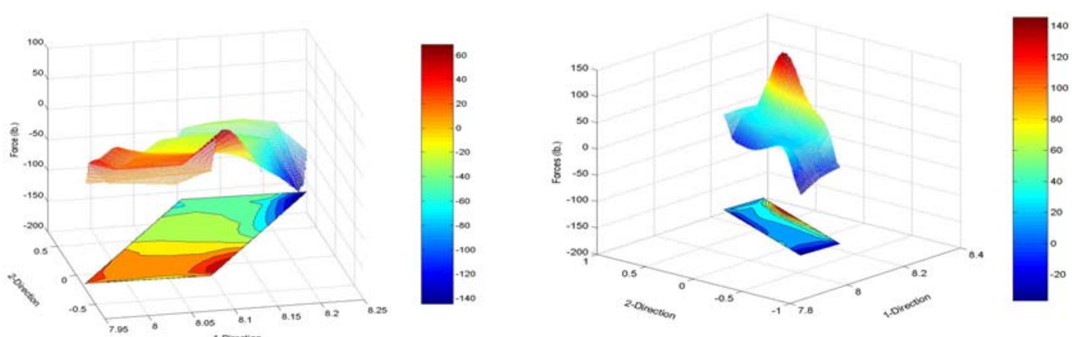
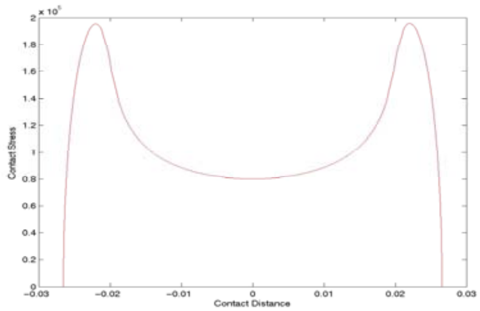


Figure-9 Contour and 3D-mesh representation of the tangential force at the contact surface.

The tangential force for blade B shows much higher amplitude that that for blade A. Further, calculating the normal force and the two tangential forces (i.e. along the two-dimension of the plan), Figure 8 shows the forces along the three directions as they vary along the slice. Note that the highest force magnitude is located near the edges. Further, the distributions of the tangential force at the contact surface are shown in Figure 9 using contour plots and 3d-mesh representation at a given time. Note that the force concentration is near the corners of the contact surface for the right and left side. Finally, using the computed forces from the aeroelastic analyses using a coarse mesh, the hybrid technique computes accurately the contact stress at the dovetail of the blade using CAPRI, which is SIE based code, assuming flat with rounded two-dimensional pad-substrate configuration. For example, the shear contact stresses for blade B are shown in Figure 10 using the most conservative loading conditions obtain from the aeroelastic analyses.



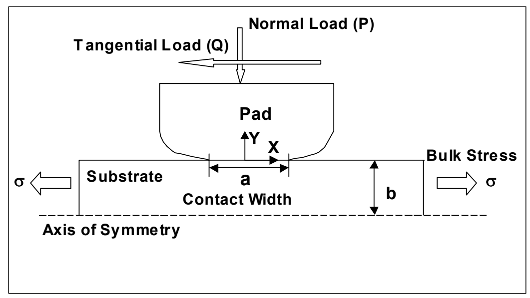


Figure-10 Shear contact stress for flat with rounded ends configurations using CAPRI code.

4- CONCLUSION

The present paper developed an efficient hybrid technique that combines finite element and SIE approach. The technique is capable of investigating fretting fatigue of an actual blade under realistic aeroelastic operation conditions. It computes the contact stresses efficiently, and utilizes it to predict the fretting fatigue life. To demonstrate the practical applications of the hybrid technique, it is used to investigate two blades, A and B, and compared their results. Under the same loading conditions, the results show that Blade B encounter limit cycle oscillations leading to a much higher forces at the contact surfaces as well as higher contact stresses. This indicates that blade B will have shorter life than blade A as observed in real life maintenance records.

REFERENCES

[1] McVeigh, P.A., Harish, G., Farris, T.N., and Szolwinski, M.P., "Modeling Interfacial Conditions in Nominally Flat Contacts for Application to Fretting Fatigue of Turbine Engine Components," *International Journal of Fatigue,* Vol. 21, (1999), pp. 5157-5165

[2] Ciavarella, M., "Indentation by Nominally Flat Indenters with Rounded Corners," *International Journal of Solids and Structures,* 36, (1999), pp. 4149-4181.

[3] Hartle, M.S., Farris, T.N., Matlik, J.F., and Rajeev, P.T., "A Hybrid Approach to 3D Edge of Contact Stress Analysis using Singular Integral Equations," *Proceedings of the 2001 National High Cycle Fatigue Conference,* Jacksonville, Fl., (2001)

[4] Gallagher, J.P., *et al.,* "Improved High Cycle Fatigue (HCF) Life Prediction," *AFRL-ML-WP-TR-2001-4159*, (2001)

[5] Hills, D.A., Nowell, D., and O'Connor, J., "On the Mechanics of Fretting Fatigue," *Wear*, Vol 125, (1988), pp. 129-146

[6] Murthy, H., Farris, T.N., and Slavik, D.C., "Fretting Fatigue of Ti-6Al-4V Subjected to Blade/Disk Contact Loading," *Materials Science Research International Special Technical Publication: Materials Science for the 21st Century,* Osaka, Japan, (May 2001), pp. 200-207.