Preventing Fretting Fatigue in Blade Dovetail Roots by Modifying Geometry of Contact Surfaces

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Introduction

Dovetails, gears, and splines have been widely used in aero engines where fretting is an important failure mode due to loading variation and vibration during extended service. Failure caused by fretting fatigue becomes a prominent issue when service time continues beyond 4,000 hours. In some cases, microslip at the edge of a contact zone can reduce the life by as much as 40–60 percent (Ref. 13).

As compressor and turbine blade speeds have increased with a reduced number of highly loaded stages, the root designs have moved from pin-fixed blades to either axial or circumferential dovetails. Axial dovetail fixings are usually employed in the design of the large civil fan blades, and for the front stage of either a military or commercial core compressor where sufficient edge-wise bending strength is required to meet demanding bird impact or foreign object damage. Circumferential blade root fixings have been used extensively by Pratt & Whitney and General Electric for many years in their gas turbine designs. It is a relatively new rotor blade attachment feature for Rolls-Royce for their compressor designs in both military and commercial applications.

On these blade root fixings, fretting can occur on the blade-to-disk contact faces of both components. Failure due to fretting in compressor/fan dovetail assemblies—manufactured from titanium alloys—is most often observed. With the increase of service time and reliability requirements of aero engine components, fretting fatigue should be paid more attention. Fatigue has always been a difficult and widely studied field, and introducing fretting complicates it further. While a means for completely eliminating fretting has yet to be discovered, many methods have been suggested that increase life considerably (Ref. 5). Suitable care taken at the design stage to avoid known causes of fretting will minimize subsequent problems. One option the designer can control is the geometry of the interface, which is an important factor affecting contact stress and fretting behaviors.

Main Mechanisms in Blade Root Fretting

Blade root fretting can be divided roughly into two types, based on the relative movement between the root and slot. This movement can be seen because of the differences in thermal expansion and contraction between the contacting surfaces of blade root and drum groove. The vibrational modes of the blades and drum will also result in a slight, relative motion between the blade root and the disc slot surfaces, thus causing energy to dissipate and, in turn, lowering the amplitude of the vibrations. These factors are combined with the various rotating parts of the gas turbine, which themselves are also subjected to centrifugal loads during engine operation.

Such centrifugal loads will be either continuous or alternating, due to the different stages of the flight. The rotor disk can expand because of thermally induced loads, as well as mechanically induced centrifugal loads (Ref. 12). The severity of all types of fretting is, amongst other factors, a function of the movement present and the crushing stress; i.e.—for a given, relative movement, the degree of fretting will increase with the crushing stress.

High cycle fatigue. This failure mode can occur with aerofoil excitation in either flap or torsional modes, and it is the type of fretting most likely to result in problems of fretting fatigue (Ref. 3). The severity of this type of fretting can be minimized by ensuring that the crushing stress does not exceed the critical property level for either in-contact material. In a frettage environment, high crushing stress can more readily lead to fatigue problems (Ref. 15). Root or under-platform damping is normally employed to reduce the blade frequency (Ref. 10).

Low cycle fatigue. This is caused by minute, radial relative movement between the blade root and disk, resulting in cyclic variation in slot width. With axial root fixings, circumferential growth of the disk rim on engine run-up causes dilation of the slot, allowing the root to move radially outwards. During the rundown the slot will close, forcing the root to return to its original position. With circumferential root fixings, the pattern of low cycle movement is more complex; as the disk or drum material carrying the groove is subjected to hoop stress, this, combined with centrifugal loading, will promote circumferential elongation of the groove during running. The blade root, however, is not subjected to hoop stress; this will result in microscopic relative movement/circumferential movement. There is also the possibility of some radial movement if the rotor construction enables the groove to "open" under conditions of bending or tension generated during running. This low cycle-type of movement can occur in combination with high cycle vibration, and can cause fretting in its own right, as often seen on the roots of "dummy" blade weights used on cyclic rigs where no aerofoils are present. Fretting can cause a considerable reduction in the fatigue strength of the materials involved, with titanium being particularly prone to this problem (Ref. 2). Therefore every effort should be made by the designer

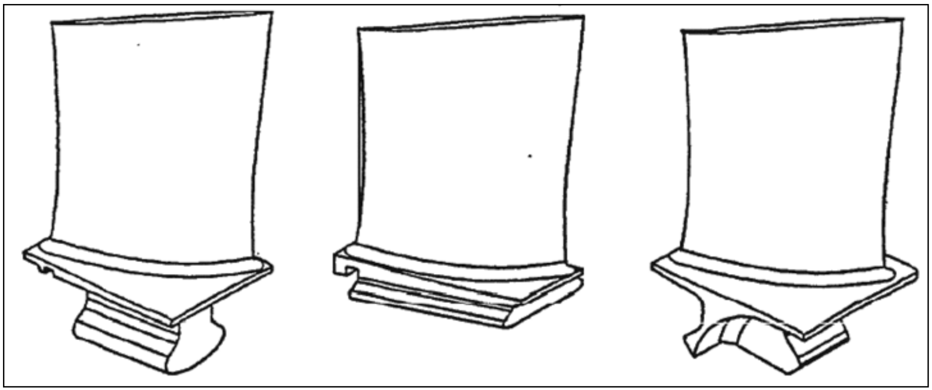

Figure 1 Diagram showing different types of blade root fixings with extended axial, non-extended axial and circumferential root dovetail with full-flank seal wings, from left to right.

to control the fatigue effects of fretting in highly stressed areas.

Microslipping at Edges of Interface

Slipping on a microscopic level will most likely occur at edges of the interface between the blade root and the slot of the disc, dictated simply by how the contacting faces behave. The coexistence of zones of sticking and microslipping is possible because of the deformable nature of the materials involved in the contacting areas, and because of the deformation pattern being such that it allows slip at the extremities of the contact zone. This argument states that even when no macroscopic motion occurs, some degree of microslip will exist and thus give rise to fretting (Ref. 6). For more complicated geometries, like the blade root interface with the blade and drum, these arguments, according to Halling (Ref. 6), are still qualitatively correct, and microslip will occur at the extremities of the contact zone.

Gabor Csaba (Ref. 4) has written a thesis that includes theoretical modelling, analysis and optimization of friction dampers. He writes of a damper model that had been developed named the "bar" model, which is a development of an existing damper model; this model has the ability to account for microslip. The bar model is relatively simple, yet complete enough to show the most important properties of a microslip friction interface like the interface between a blade root and disc.

Csaba's ideas are fundamental in understanding how blade roots cause frettage if we were to treat the interface between the blade root contacting the disc in the same way Csaba treats friction dampers as a bar model acting on a plain surface.

The behavior of the fretting mentioned (Ref. 4) demonstrates and details how the contact region experiencing microslipping can fluctuate by increasing and decreasing in area, and the rate of this fluctuation could have an effect on the rate of fretting and/or fretting fatigue. Csaba describes how this fluctuating area of microslipping grows and moves towards the center of a contacting region as the tangential loading increases. Then as the tangential load decreases, this area of microslipping will begin to shrink away from the center, back towards the edges of the contact zone (if macroscopic sliding doesn't occur).

As the blade root and drum elastic constants differ, and given that the drum's size is much greater than the blade, all of the components' stiffness will differ relative to the other components; slip may then occur under a normal load due to centrifugal loading. The blade loadings (both tangential and centrifugal) on the top-side of the blade root, and the walls of the groove, will fluctuate due to changes in engine speed and compressor revolutions. This cyclic loading alone may induce microslip and promote fretting damage—thus inducing fatigue cracks in the fretting zone (Ref. 16). The failure of the blade root is caused by frettage fatigue cracking of the root, which then acts as a stress concentration. The crack can then propagate across the root due to high cycle fatigue, ultimately leading to complete failure of the blade.

We also need to consider the effects of friction damping and how it promotes fretting fatigue. Friction damping in blade dovetail attachments is often dominated by the microslip properties of the dovetail interface (Ref. 11), and because it has been shown that microslip can occur at the interface, it then must be decided whether friction damping is a curse or a blessing.

Allen, in his paper, "Friction Damping in Compressor Blade Dovetail Attachments" (Ref. 1), states that if friction damping is to be successfully employed in preventing blade failures due to vibration, then fretting wear and fretting fatigue must be seriously taken into account and given equal consideration relative to the benefits of friction damping.

While friction damping is evidently advantageous in limiting blade-resonant vibration, Lazan (Ref. 9) has highlighted in his *Damping of Materials and Members in Structural Mechanics*, that:

"For the case of dry interfaces (metal-to-metal contact) coulomb friction provides an important mechanism for dissipating energy under cyclic shear displacement. However, a joint optimized for maximum dry-slip damping is generally subject to serious fretting and corrosion effects in those interface regions having large cyclic slip. Such interface surface deterioration may cause the joint to drift from the optimum conditions of damping and may also initiate fatigue cracks, i.e.—the type of damage that high damping in a system exposed to resonant vibration is intended to mitigate. The cure may therefore lead to problems worse than the original problem (Ref. 9)."

Reducing Fretting Action by How the Contacting Surfaces Interact

Johnson (Ref. 7) says that an ideal solution to the problem of fretting is to eliminate all possibilities of microslip. In Johnson's textbook *Contact Mechanics* (Ref. 7), he states that two lessons can be learned about avoiding microslip and ensuing fretting:

1. "(The) design should be arranged so that the line of action of the oscillating force is close to the direction of the common normal of the two mating surfaces."
2. "(The) profiles of the two contacting surfaces should be designed so

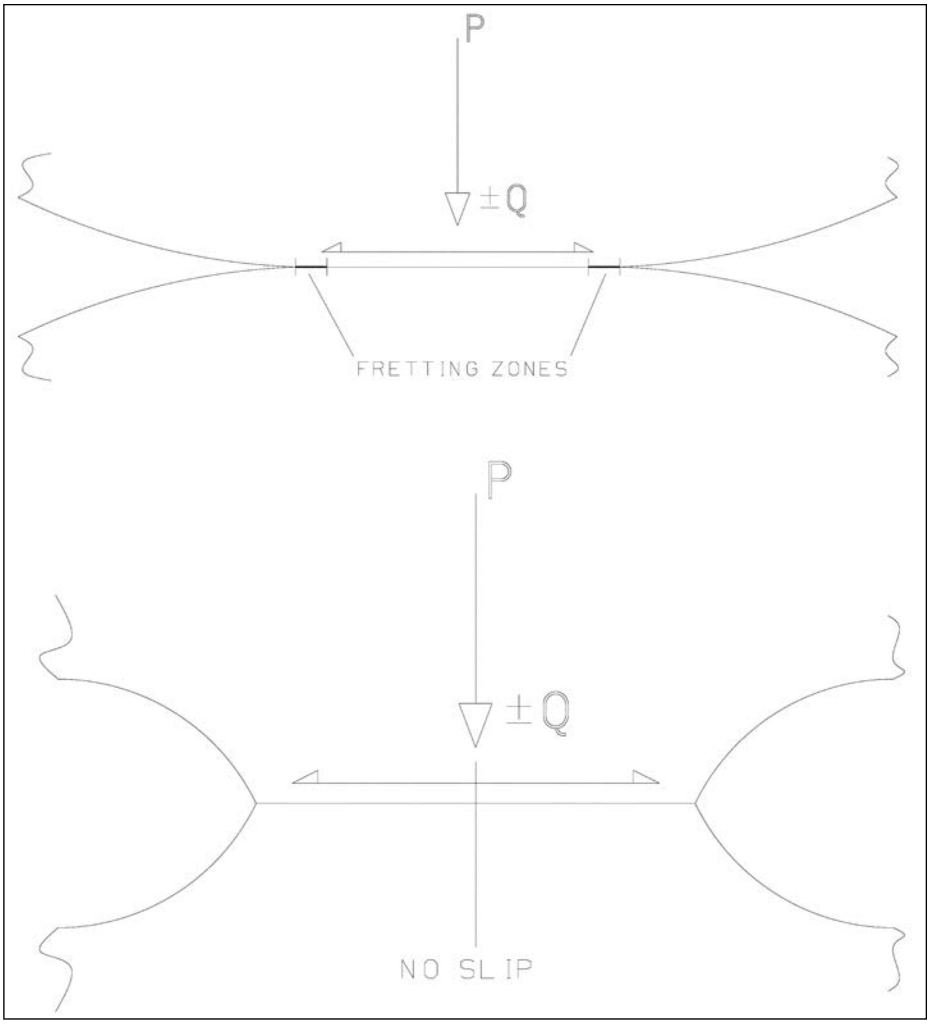

Figure 2 Top diagram shows common contacting surfaces; bottom diagram shows the "ideal" design solution (Ref. 7).

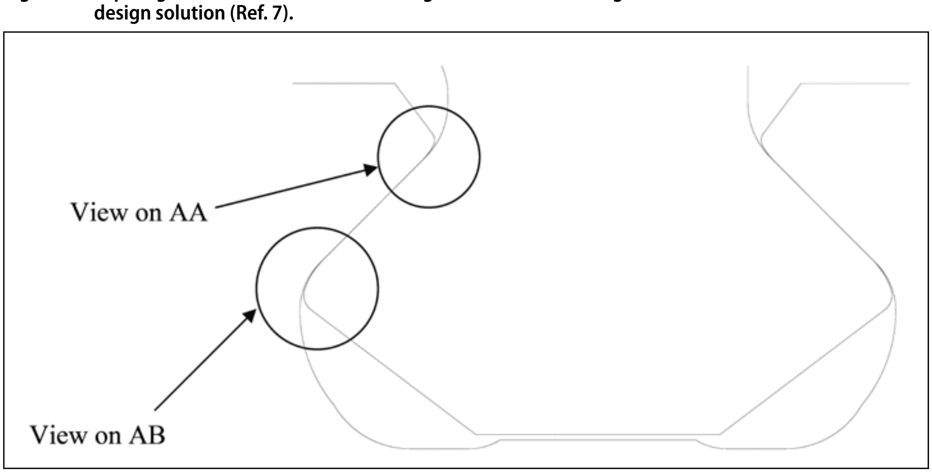

Figure 3 A typical circumferential blade root interface.

that, when they are in contact and under load, high concentrations of tangential traction at the edge of the contact area are avoided (Ref. 7)."

Figure 2 shows the influence of the profiles of contacting bodies on microslip and fretting. The top of Figure 2 shows how fretting occurs from common contacting bodies. The blade root has radii, or arcs, as part of its profile, so a similar scenario could occur when the root is pressed against the wall of the slot in the disc. The bottom diagram (Fig. 2) is the ideal design scenario. This means that any "sharp-notches," which can arise at the edge of the contact of non-conforming surfaces, are to be avoided.

Re-Design of Blade Root to Reduce Fretting Fatigue

The methods of eliminating microslip learned from Johnson and O'Connor (Ref. 8) could possibly be applied to the actual blade roots themselves to prevent failure from frettage fatigue. It is not uncommon that small microcracks may propagate straight across the blade root and cause separation and total failure of the blade. If we were to eliminate microslip at the edges of contact between the axial/circumferential blade and disc slot, perhaps such fretting action could then be prevented—as well as failure from fretting fatigue and HCF (high cycle fatigue). Waterhouse (Ref. 14) states that the influence of the actual geometry of the contacting surfaces can greatly influence the design application. It is agreed that the incidence of fretting fatigue failure could be greatly reduced by attention to the design of contacting components at the drawing board and design stage of the blade root interface.

Figures 3–5 show what the contact surfaces look like for a typical circumferential blade root interface.

Figure 4 shows that the radius or exterior arc on the top of the root of the blade could be forced against the inside radius/interior arc on the slot of the disc due to HCF loading. Due to the fact that the materials are deformable and the CF is not constant, but fluctuating, the material is most likely to experience microslipping within this small region. As explained before, the fluctuating growth of the microslipping area from the edges towards the center of a contacting region as the tangential/centrifugal loading increases, and then the shrinking of the microslipping area back from the center to the edges of the contact zone as the tangential/centrifugal load decreases, will most likely cause fretting at point AA.

Point AA, near the top of the dovetail flanks, is where most failures are seen on blade roots due to fretting fatigue. Allen (Ref. 1) has also shown that cracks can originate and propagate across the same spot, but on the slot of the disc—not just the blade.

At point AB (Fig. 5), the root of the blade will CF outward and fret against the wall of the slot on the drum (as described above); this is due to the deformable nature of any elastic material, like titanium.

If you were to remove some of the material by a chamfer, for example, to allow the blade root/disc slot to deform in these areas, then the material cannot rub/fret against anything, as the material has been removed. Figures 6–8 show how microslip could be eliminated by the use of a chamfer machined across the blade root to reduce any high concentrations of tangential traction at the edges.

Microslipping and therefore fretting could possibly be eliminated if the materials are allowed to deform due to the fluctuating centrifugal loads, but not contact one another.

The fretting at the upper edge of the bearing surface (points AA and AB) can initiate a small crack, which may propagate to failure if the alternating bending stress due to blade vibration is large enough. According to Waterhouse (Ref. 14) the undercutting of the neck of the dovetail could increase the fatigue strength of the blade by a factor of two.

Waterhouse states that the use of a relief radius at the flank edge greatly improved the fatigue behavior, and can prevent initiation of fatigue cracks. Figure 9 shows how the Waterhouse relief radius can be incorporated into the circumferential blade root design.

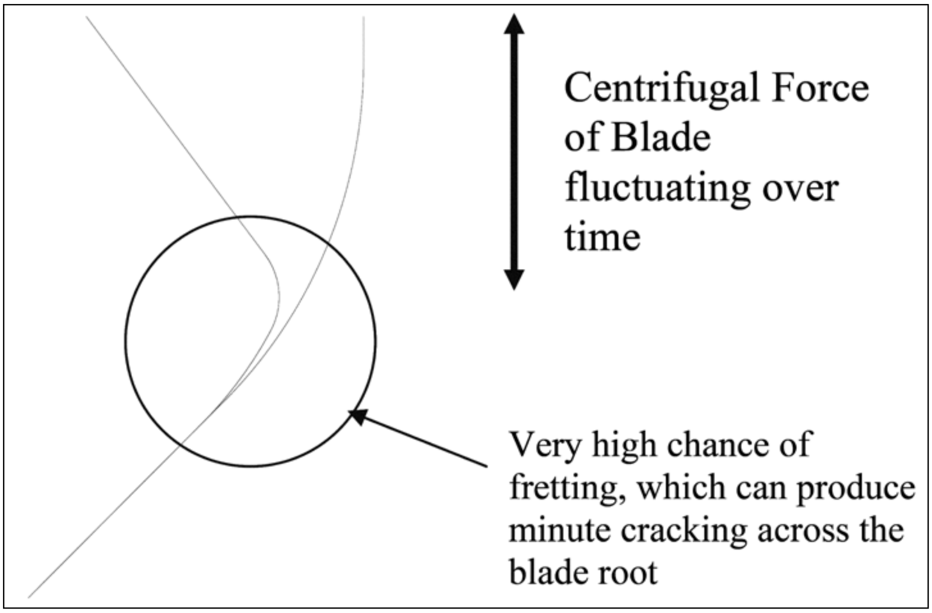

Figure 4 View of Point AA.

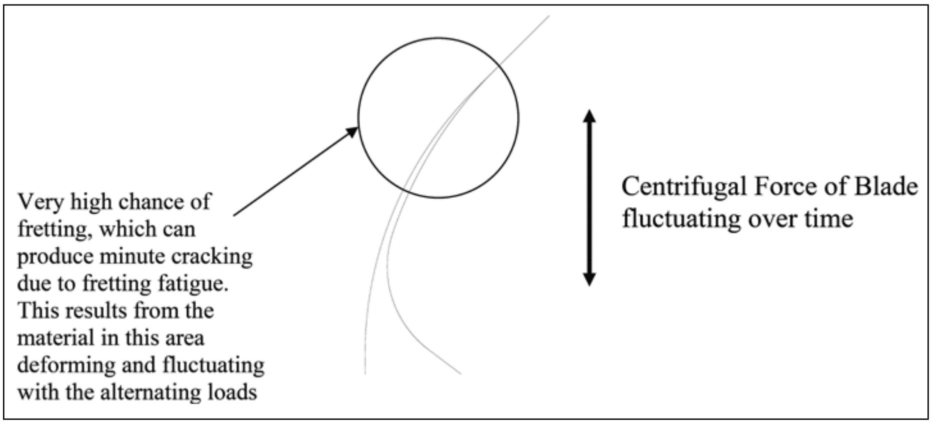

Figure 5 View of AB.

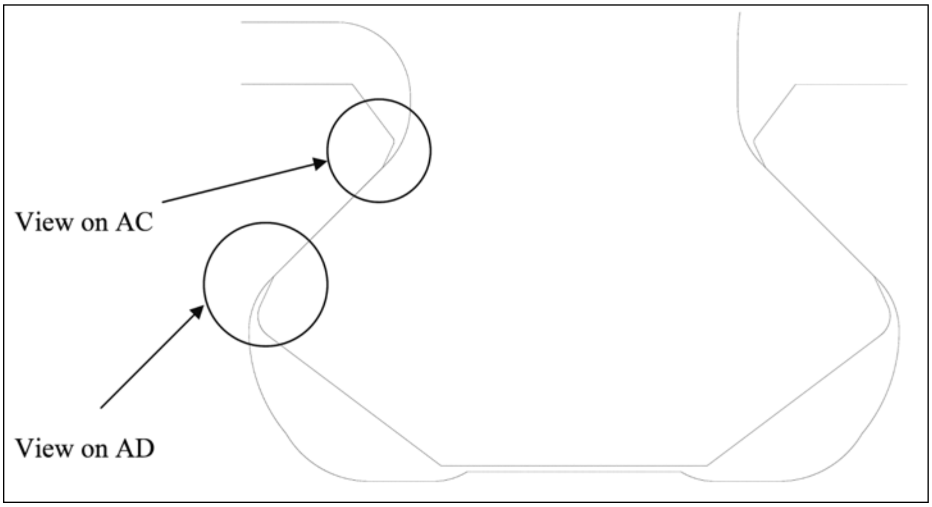

Figure 6 The use of chamfers to eliminate microslip, therefore fretting.

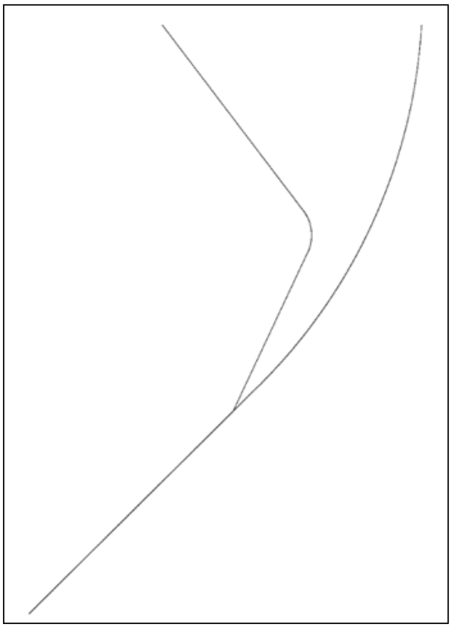

Figure 7 The use of a chamfer to eliminate microslip at Point AC.

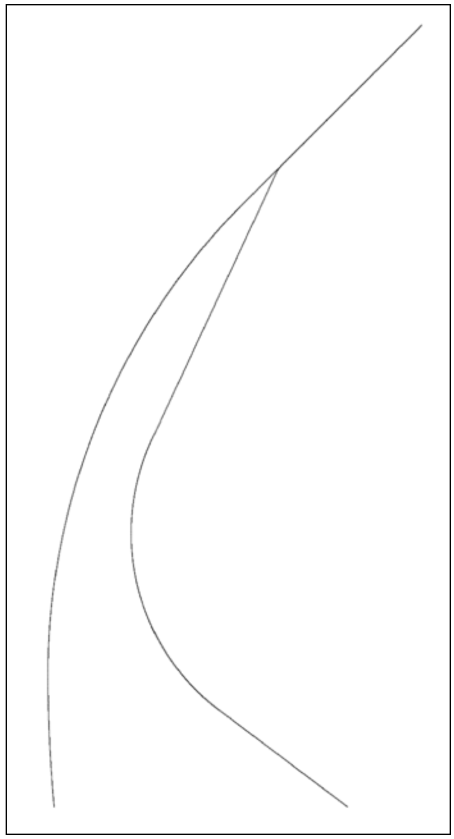

Figure 8 The use of a chamfer to eliminate microslip at Point AD.

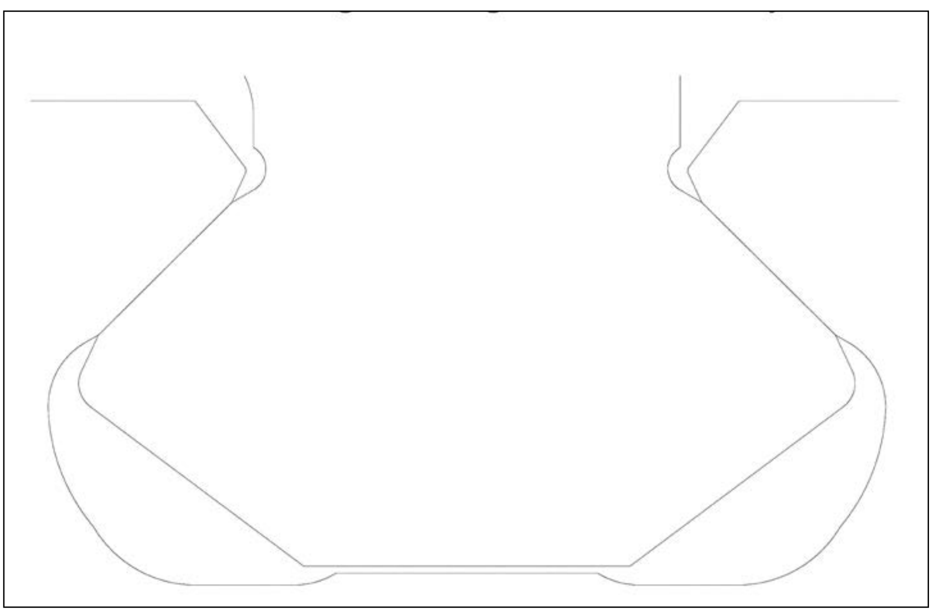

Figure 9 The use of an undercutting and a relief radius on the blade slot and the slot of the disc.

Simpler Method of Manufacture

Another advantage of this design is the fact that the geometry is now simpler. Usually the edges of the blade root are manually rounded. But now that the rounded edges and arcs are gone and replaced with flat chamfers, it is simpler and easier to manufacture and can be reproduced many times on different blade roots. The dependence on the skill of a technician and the variations in dimensions due to different technicians' abilities, etc., is completely removed. The contacting faces on the blade and inside the slot on the disc can be exactly dimensioned on a drawing, and with suitable manufacturing methods achieve the dimensions specified on the drawing. This allows the area of contact to receive equal mechanical loading between all the blades because the mating surfaces are no longer considered "Hertzian," and are now completely flat.

Other Applications

This simple modification to the geometry of the blade root can be applied to axial blade roots and circumferential blade roots on all the stages of a gas turbine compressor, including the main fan stage. This geometry can also be applied to the fir tree roots of turbine blades. Another application is for involute gears, where it could possibly prevent fatigue in the roots of gear teeth. **PTE**

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