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SIMULATION OF DEFORMATION MODES FOR DAMAGE DETECTION IN TURBINE ENGINE DISKS

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Abstract

Recent studies have shown that analytical predictions of crack growth in rotating components can be used in conjunction with displacement measurement techniques to identify critical levels of fatigue damage. However, investigations of this type traditionally have focused on the detection of damage at known flaw locations. This paper addresses the related problem of estimating damage associated with flaws at unknown locations, through the combined use of analytical models and measured vibration signatures. Because the measured data are insufficient to identify a unique solution for the location and severity of fatigue cracks, the analytical procedure must be able to bound the extent of damage occurring at life-limiting locations. The issue of analyzing successive measurements to improve estimates of worst-case damage and crack locations also is discussed.

Introduction

One of the more attractive applications of material prognosis technology is the life management of turbine engine disks, which are expensive to replace, difficult to inspect, and subject to complex and hostile loading environments that dictate a highly conservative retirement philosophy. The ability to monitor the damage state of such components, project subsequent damage development, and estimate remaining life would be revolutionary in terms of cost savings, safety, and fleet readiness.[1-3]

Recent experimental investigations[4,5] suggest that the prospects for damage detection in rotating components are significantly improved by averaging measured responses over a large number of cycles, and by signature monitoring based on prior knowledge of the damage modes of interest. In what follows, we discuss the use of analytical models to provide accurate information for use in the pattern recognition process leading to damage detection. The study uses a mock compressor disk model in which known damage states can be introduced to generate baseline signatures for probable damage modes. The same disk model is used here to simulate the measured data for a system containing one or more cracks whose size and location are not known a priori. Both the accuracy and the conservative or non-conservative nature of the predictions are of interest.

It should be noted that significant questions exist about the feasibility of performing adequate displacement measurements in such systems. This paper does not address measurement issues; however, experimental investigations planned for next year will, we hope, provide further guidance on sensor requirements and other practical issues.

Disk Model

Our model of a generic engine disk possesses geometric, mass, and stiffness characteristics typical of a compressor disk, but is not based on a particular production component. In the present study, we simplify the model by representing the blades only by pressures in the slots, and monitoring displacement values in the blade posts. The disk has an inner radius of 80 mm, outer radius of 205 mm, and varies in thickness between 2.5 and 20 mm. The mechanical properties are typical of a Ni-base superalloy ($E = 200$ GPa, $\nu = 0.30$, $\rho = 8{,}300$ kg/m^3), and the nominal rotation speed is 10,000 RPM. Figure 1 shows the cross-sectional shape of the disk.

Figure 1. Generic Disk Model Cross Section.

The complete disk model consists of 24 nominally identical sectors, represented by copies of a single substructure spanning 15 degrees of arc (Figure 2). Each sector contains a single 10-mm hole in the web, and two blade slots. To introduce a crack, we create a modified version of the basic substructure in which the crack is represented in detail, using the Zencrack[6] software to generate focused meshes with quarter-point finite elements surrounding the crack tip. Figure 3 shows a close-up view of a deformed mesh in the neighborhood of a crack. The use of the detailed crack tip mesh allows the extraction of accurate stress intensity factor data in the cracked area(s). A complete disk model containing a single crack consists of 23 identical uncracked substructures and a single cracked substructure. The external nodal connections in the cracked and uncracked sectors are identical; therefore, introducing one or more cracks is as simple as specifying a different substructure name to replace an uncracked sector. The analyses are performed using ABAQUS.

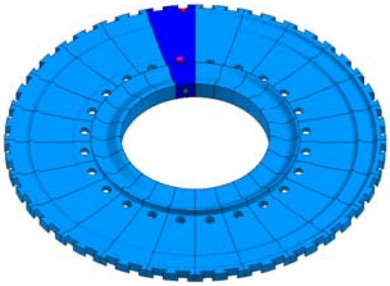

Figure 2. Substructured Generic Disk Model.

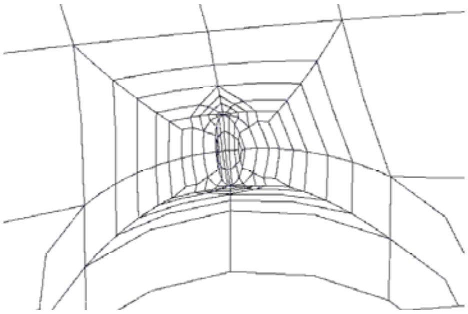

Figure 3. Detail of Deformed Crack Mesh near Hole Edge.

Crack Signatures

Both "known" data (displacement signatures for cracks with known location and size) and "measured" data are generated in this study using the same library of substructures. However, our simulated "measured" data contain crack locations and sizes that are not represented in the baseline data.

Baseline crack signature data have been created for single cracks of various sizes in the disk bore, at the edge of the hole in the web, and in the base of a blade slot. The bore crack is elliptical, and located in the axial center of the bore. The hole and slot cracks are semicircular corner cracks. In each location, baseline crack signatures corresponding to crack lengths of 1.00, 2.25, and 3.50 mm have been predicted, providing a library of signatures for known damage types (Figure 4). In each case, the crack is located in the sector with one edge at an angular position of zero degrees. In all cases, the signatures characterizing damaged states of the disk consist of values of *displacement deviations*, or differences between the measured displacement and the steady-state value for the undamaged system.

Notice that the signatures for cracks in various locations are distinctive, in the sense that they each involve quite different combinations of harmonic components. Note also that for the slot cracks, which are very near the sensor location, the peaks in the signatures are highly localized, while those further inboard exhibit more gradual variations. The amplitude of the signature for a given crack type varies nonlinearly with crack size. Corresponding to each displacement signature in the library of known damage states, in addition to the crack size and location, is a value of the appropriate stress intensity factor for use in crack growth estimation. If a measured signature can be identified with a series of conditions in the database, it is possible not only to estimate a crack size, but also to interpolate for the corresponding stress intensity factor and crack growth rate.

A word is in order regarding the magnitudes of the displacement deviations in the signature plots of Figure 4. While the displacement magnitudes are quite small, it should be noted that the data are obtained from a model of the disk only, rather than the complete rotor system. In a model of the disk alone, the asymmetry in response caused by the stiffness variation in the cracked disk cannot be determined, since it depends on the mass and stiffness characteristics of the complete rotordynamic system. Instead, one must constrain the rigid-body displacement corresponding to the shaft whirl mode to stabilize the model. Unfortunately, this displacement component is the most significant artifact of the damage in the real system, and we are limited to analyzing the higher-order harmonic components, which are quite small. In the tests described in Reference 4, it was indeed possible to measure the asymmetric displacement components and to correlate the measured signatures with analytical predictions of the probable damage mode; thus, there is evidence that such a measurement is achievable, at least in the setting of a spin pit test.

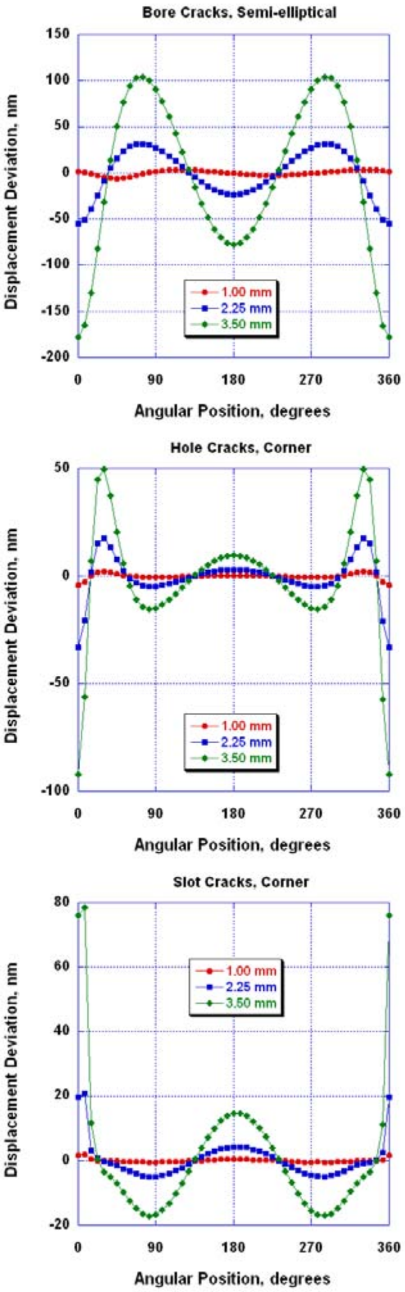

Figure 4. Baseline Signatures for Known Crack Configurations.

Additional analyses have been performed using multiple copies of the same disk model attached to a relatively rigid shaft constrained by bearings at the ends. At 10,000 RPM, the nominal radial displacement magnitude is 130 µm, while the shaft whirl displacement amplitude is 40 µm. When these components are filtered out, as in the single disk analyses, the remaining displacement amplitudes tend to be on the order of 1 µm or less. Further experimental investigation of realistic rotor systems is needed to establish the feasibility of measuring the displacements with sufficient accuracy for damage mode identification.

Signature Filtering and Processing

In this investigation, we have assumed that a blade tip clearance sensor, such as a capacitance or eddy current probe, is used to collect radial displacement data from the disk. Therefore, the damage modes are characterized by the deviation of the radial displacement from the nominal steady-state value. In the single disk model used for most of the calculations, the first harmonic of the radial displacement, which corresponds to the rigid-body shaft whirl displacement of the disk, is purely an artifact of the model constraints and is filtered out of the results. The procedures we describe for analyzing the measured data are general, and would be identical if the first harmonic components were present.

For both the baseline (known damage) and "measured" cases, we begin by calculating Fourier transforms of the radial displacement data. The displacement amplitude in sector 'i' of the disk can be expressed in the form

$$U_i = U_0 + \sum_{k=1}^{N} A_k \cos\frac{2\pi k}{N}(i-1) + B_k \sin\frac{2\pi k}{N}(i-1)$$

in which A_k and B_k are the Fourier coefficients. The magnitude of the k^{th} harmonic component is $C_k = \sqrt{A_k^2 + B_k^2}$. The *relative* magnitudes of the harmonic components C_k are significant in determining the type of damage mode under consideration, while the absolute magnitudes are important in determining the extent of the damage. The phase differences (related to the ratios A_k/B_k) indicate the location of the damage site around the circumference of the disk.

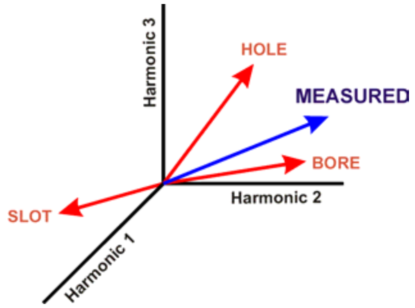

Figure 5. Signature Directions in Harmonic Coordinate Space.

We first characterize the measured signal by its *direction* in the space of harmonic coordinates (Figure 5). In this step, both the measured signal and baseline damage signatures are normalized to unit magnitude, and the projection of the measured signal onto each of the reference signatures is computed. The nearest neighbors of the measured signal are selected as candidates for further analysis. It should be noted that Figure 5 is somewhat oversimplified: the signatures for known cracks of different sizes at a given location do not point in precisely the same direction, but do tend to cluster in a relatively small region of the harmonic space.

For each candidate damage mode, a series of signatures is next extracted from the database for similar cracks of different sizes for use in interpolation. Figure 6 shows a simple example in which the signal amplitudes of bore, hole, and slot bottom cracks of various sizes might be used to estimate crack length for a given signal amplitude. Frequently, and particularly when multiple cracks are present, more than one of these groups might be used to obtain a crack length estimate for a single measured signal. Once the estimated crack length is known, one can interpolate from the corresponding data for stress intensity factors to obtain rough estimates of K and crack growth per cycle (Figure 7).

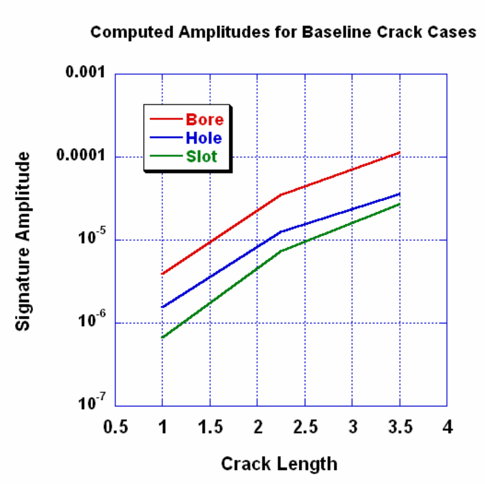

Figure 6. Inverse Interpolation for Crack Length Estimate.

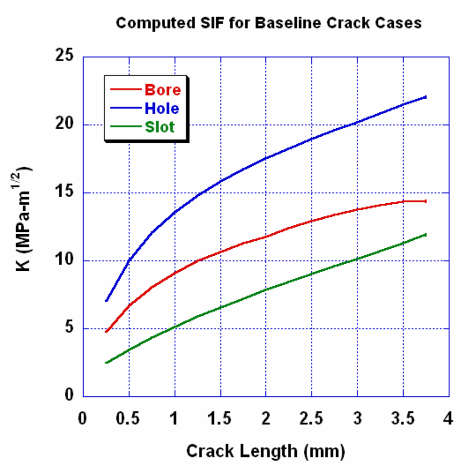

Figure 7. Stress Intensity Factor Estimate from Crack Length.

Damage Estimates

Damage estimates have been performed for numerous cases, with the "measured" data being produced using substructured models similar to those used for the baseline analyses. Simulated disk measurements have been generated for configurations with single and multiple cracks (up to three), and for crack sizes different from those in the database of known damage conditions.

Crack length estimates based on selection of the single damage mode closest to the measured signal in harmonic space (nearest neighbor) are shown in Figure 8. Notice that the crack length estimates are quite accurate, but in some cases the estimates are non-conservative. The reason for this is that some estimates, especially for multiply-cracked disks, are based on crack types or locations that are not correct. Using several nearest neighbors to make multiple estimates does result in conservative predictions, as shown in Figure 9. In practice, we would anticipate augmenting the database of known damage conditions as time progresses, which would allow the prediction to converge on the correct mode of damage after several successive measurements. A second benefit of this approach is that the tolerance on projections used to formulate damage estimates almost certainly can be reduced as more damage conditions are added to the database, resulting in a sharper estimate of the mode and extent of damage.

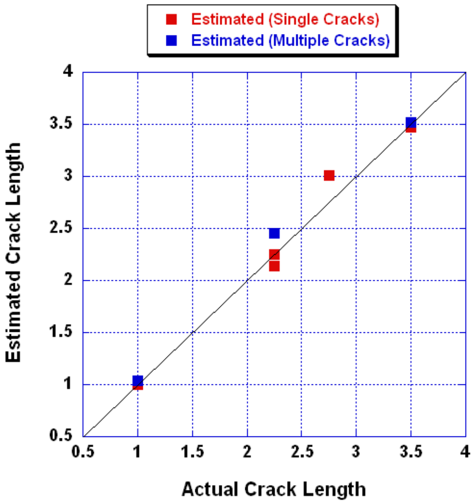

Figure 8. Crack Length Estimates from Nearest Neighbors.

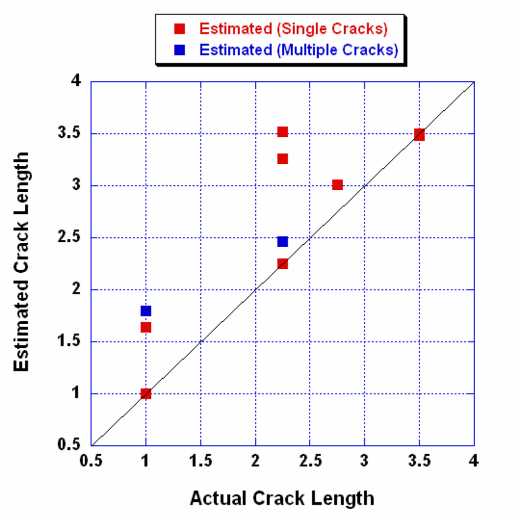

Figure 9. Crack Length Estimates based on Multiple Neighbors.

Summary and Conclusions

A substructure-based analytical testbed has been created to study the problem of identification of cracking damage in turbine engine disks. The substructuring approach makes it relatively simple to model the damaged regions in detail, thereby allowing estimates not only of crack location and size, but also of stress intensity factors and likely crack growth rates. Identification of the damage modes in a measured signal is accomplished by analyzing the Fourier-transformed signature and that of several known damage modes residing in a database for the component of interest. The direction of the transformed signal in harmonic space indicates the probable type and location of the crack; using known signatures for cracks of the same type, estimates of the crack size are obtained through interpolations based on the amplitude of the measured signal.

A particularly important use of the present methodology is in refining one's estimate of the type, location, and extent of damage as data become available at successively later times. In the process, additional relevant damage modes for the component can be analyzed and added to the database, as needed, to help sharpen the estimation of the probable damaged condition.

Further analyses of multiple-disk systems, as well as experimental investigations, are needed to establish the feasibility of measuring displacement data to the accuracy required for reliable assessment of damage evolution in engine disks. Some experiments of this type are planned for the next calendar year. The consideration of blade vibrations is a further area of interest because of the rich harmonic content introduced into the measured data. Depending on the characteristics of particular systems, it may be possible to monitor disk damage, blade damage, or both from a given type of displacement sensor. The feasibility of each of these options must be assessed to define a logical approach for managing the remaining life of the complete system.

Acknowledgement

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