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MATERIALS AND STRUCTURES PROGNOSIS FOR GAS TURBINE ENGINES

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ABSTRACT

Gas turbine engine diagnostic systems often utilize data trending and anomaly detection to provide a measure of system health. These systems provide significant benefits for trending shifts in engine performance and diagnosing system degradation that requires some maintenance action. However, this approach may be limited in the ability to uniquely identify damage for select components and failure modes. Advanced prognostic systems are being developed to work symbiotically with state of the art diagnostic techniques in use today; these advanced systems use advanced material and component damage evolution modelling linked with system-level structural analyses to intelligently guide the health management system to search for specific signatures that would be expected from key changes in component and system health [1,2,3,4].

Material damage models, advanced component models, and novel system-level structural analyses are being used to generate newly defined "structural transfer functions" (STFs) that provide a link between sensed parameters and the remaining capability of specific components, and the system. The characteristic damage signatures vary by component type and failure mode, and hence the specific STF approach varies among component types. An initial STF approach was developed and demonstrated for a specific component and damage type [5] under an initial feasibility program. This STF-based prognosis approach is fundamentally different from the traditional modal analysis based NDE approach used for crack detection. This presentation will review this novel STF-based prognosis approach, and consider examples of STFs characteristic of specific components and damage types, as well as progress towards the development of tools that are enabling system-level STF development [6].

NOMENCLATURE

STF	Structural Transfer Function
PHM	Prognosis & Health Monitoring
LCF	Low Cycle Fatigue
HCF	High Cycle Fatigue
CMS	Component Mode Synthesis
TOA	Time of Arrival
NDE	Non Destructive Evaluation
a	Crack Size
N	Number of Cycles

MATERIALS AND STRUCTURES-BASED PROGNOSTIC APPROACH

The concept of a materials and structures-based prognostic approach is relatively straightforward, and may best be described by breaking the approach into two key steps. The first step is the quantitative correlation of some sensed parameter to the current damage state of a component. For example, relating sensed blade tip deflection to a specific crack size at a specific location. This first step may be developed by empirical or experimental means if a single failure mode and location are of interest. However, development of numerous potential STFs for a comprehensive PHM system by experimental or empirical means would be prohibitive in terms of cost and time. Following sections will demonstrate analytical approaches that Pratt & Whitney has developed for generating these unique STFs. Further, the key features in an STF will, for some potential failure modes of interest, be somewhat subtle in nature and require that the prognostic system intelligently process the sensed parameters to search for the characteristic signatures of interest. These STFs will enable enhanced safety, by yielding signatures characteristic of emerging damage that may pose a near-term threat, as well as enable fleet management by providing measures of more evolutionary usage / life consumption.

The second key step in the STF-based PHM approach is the prediction of future capability based on the STF-defined current health state. This step involves the projection of health or remaining life based on expected or defined conditions of future use. This step requires that, as much as possible, variability and/or uncertainty be reduced in the component life predictions. Key sources of variability and uncertainty include the baseline material property assumptions, expected operational environment, as well as the life prediction tools themselves.

STRUCTURAL TRANSFER FUNCTION DEVELOPMENT FOR ROTORS

An integrated STF-based PHM capability was demonstrated by Pratt & Whitney under a DARPA-funded Prognosis tractability program [5,7]. In this program, STFs were generated to predict the expected changes in blade-tip time of arrival as a function of crack size in discrete locations of a gas turbine engine disk. This work demonstrated types of features, feature patterns, and sensitivity of these features that could be used as STFs for disk crack safety-related PHM. A series of elevated temperature spin tests were run to demonstrate the accuracy of the STFs, as well as the ability to "prognosticate" remaining life from the STF-defined state of health.

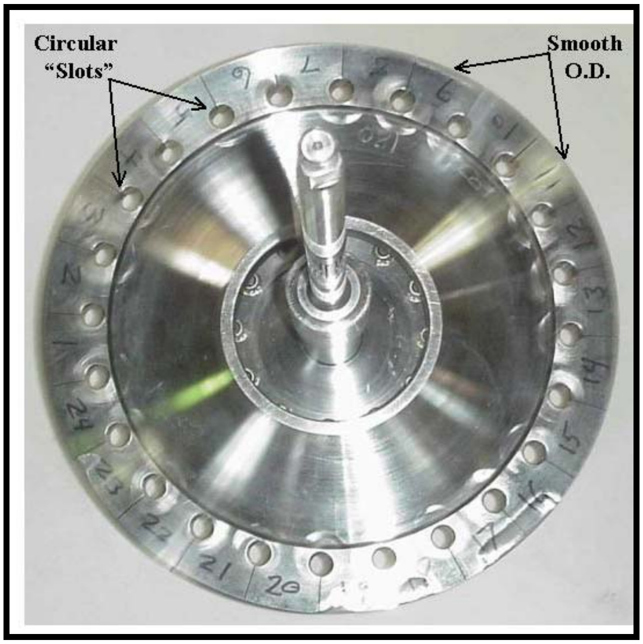

Figure 1: Photograph of Minidisk

A photograph of the component used for the first two tests of this initial work is provided in Figure 1. This simplified disk, or mini-disk, included features that simulate those of interest on an actual gas turbine disk, while providing a convenient and cost effective test vehicle. Structural transfer functions were developed for several potential crack locations on the disks. An example of the projected deformed disk shape, for a discrete crack size at a specific "lug" location is provided in Figure 2.

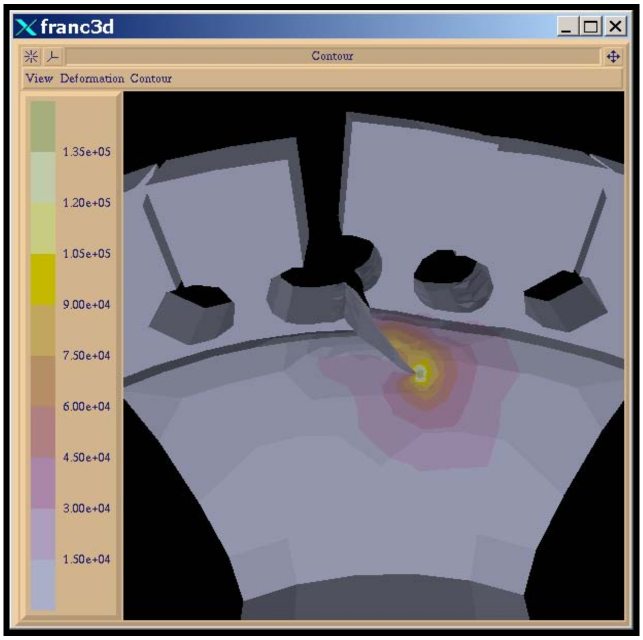

Figure 2: Deflection Pattern Associated With Lug-Type Crack

Note that for this location, the primary lug deflection pattern is isolated to a small number of simulated blade tips. The extent of this deformed pattern was developed as a function of crack size to yield a location-specific STF.

A second example of deformed shape from a bore crack is provided in Figure 3. Note the distinct differences in the global shape for this second potential crack location. As expected, the bore crack location manifested in a deflection pattern that spread over a larger number of blades. An intelligent reasoner would then be required to isolate the characteristic signature to a specific damage location, determine crack size from the STF, and then project damage severity and remaining capability.

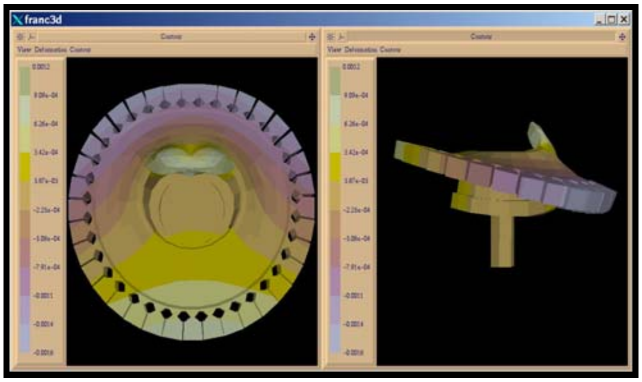

Figure 3: Deflection Pattern Associated With Bore-Type Crack

During the spin tests, these STFs were used to determine current damage state based on changes in sensed blade tip time of arrival. Knowing the operational profile projected for the remaining test sequence, the remaining number of test cycles (prior to component failure) was projected. A key test objective was to continue operation close to component failure, but stop the test prior to rupture. An example of an STF-informed remaining life projection is provided in Figure 4.

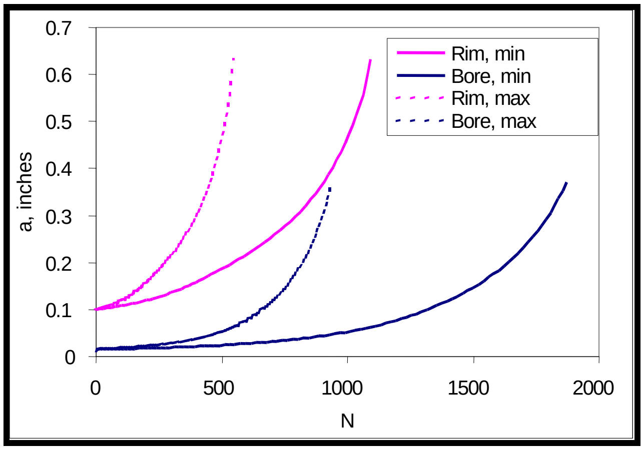

Figure 4: Life Projection from Inferred Crack Size

STRUCTURAL TRANSFER FUNCTION DEVELOPMENT FOR AIRFOILS

The types of features that comprise the location-specific STFs are highly dependant on damage type. A primary focus of recent work has been the development of STFs associated with airfoils subject to high cycle fatigue damage [8,9]. In addition to blade-tip deflection, this effort is developing and demonstrating new analytical tools to predict changes in blade resonant frequency and mode shape, as well as system-level response changes to detect and isolate blade HCF damage, and to project remaining life from these sensed conditions.

Initial work demonstrated that basic modal analysis was not always sufficient to predict changes in resonant frequency as a function of airfoil crack size. Modal analysis – a linear approach, starts with differential equations of motion, solves for eigenvalues to identify system natural frequencies and mode shapes, and determines changes in natural frequencies and mode shapes due to increasing crack size. This approach ignores damping and does not account for effects of crack face contact. As a result, modal analysis was found to be anti-conservative, which is to over-predict the expected change in frequency shift, for certain conditions. Complex modes and the presence of manufacturing-induced residual stresses can lead to crack face contact during HCF excitation. This crack face contact is not captured in typical modal analysis, and decreases the observed resonance shift.

A second approach was developed in which transient ANSYS, with crack face contact, was used to determine excitation levels at discrete driving frequencies. This process required extensive computational time before the transient driving effects died-out sufficiently to identify steady-state response amplitude. Additionally, this process required numerous analyses, each at discrete frequencies, be executed such that the "peak" driving frequency could be identified for each crack size. The process had to be repeated at each desired crack size to develop a STF that related frequency change to crack size. An example of an initial modal analysis defined response, grounded with test data, and then compared to a transient-ANSYS with contact comparison, is shown in Figure 5.

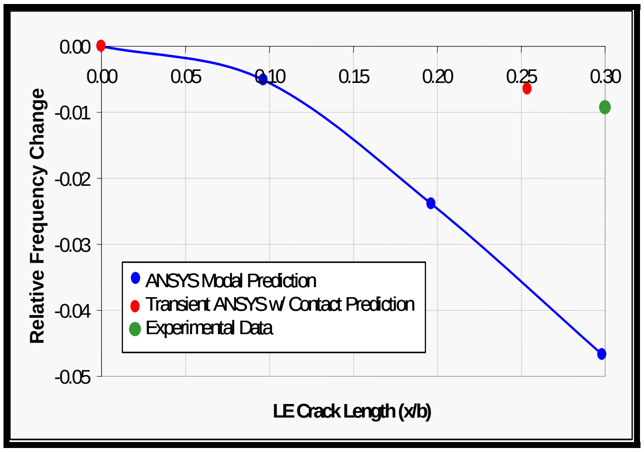

Figure 5: Initial Airfoil HCF STF

While this methodology adequately captures the physics of the damage effect on the component response, it is computationally intensive. Development of a STF for a single location on a single airfoil can take on the order of months using this process. While this might be a viable approach for analysis associated with a key failure mode, the development of a comprehensive PHM system capable of prognosticating health for numerous potential high responding modes is computationally intractable.

A third approach was developed based on a component mode synthesis technique - a reduced order modeling approach for multi-stage turbo machinery. The Component Mode Synthesis (CMS) approach begins with standard single-stage analyses, but adds a constraint mode calculation at each stage interface and a secondary modal analysis of the assembled rotor. The result is a true multi-stage calculation that accurately captures stage-to-stage coupling. This approach was demonstrated to significantly decrease the computational burden, while providing results that were highly correlated with the transient ANSYS with contact approach. These analyses were executed on the order of hours per crack location, thus providing a tool that could be utilized in the development of comprehensive PHM system. An example of the CMS to transient ANSYS result correlation is provided in Figure 6.

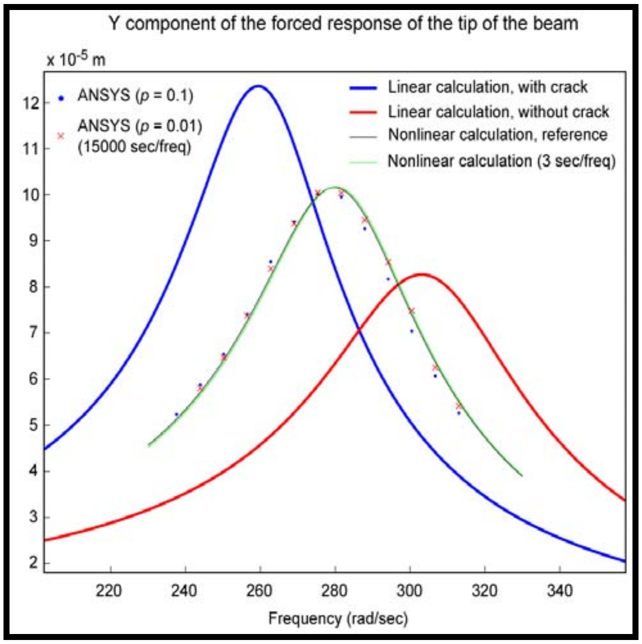

Figure 6: CMS to Transient ANSYS Correlation

SYSTEM-LEVEL STF DEVELOPMENT APPROACH

A next step beyond the development of STFs that define changes in component response due to increasing damage levels on the component of interest is the development of STFs that can correlate component-specific damage to some system-level, or remote location-specific change. While it is readily accepted that not all damage modes and types will manifest themselves in characteristic signatures that can be measured well removed from the damage location with many of the sensors and data processing techniques in service today, a critical limitation of this approach is the lack of understanding of multi-component interaction. The development of modeling techniques that can accurately define characteristic signatures as transmitted through multiple components, such that an intelligent PHM reasoner can actively search for these features.

One key building block in this system level approach is the development of efficient computational techniques capable of modeling multiple components. This requirement introduces another application for the CMS methodology. Recent work has demonstrated the ability to model multiple stages efficiently, as well as to discern component-coupling effects, previously unable to be understood when forced to rely on single stage models. An example of the multi-stage interactions captured using the CMS approach is provided in Figure 7. This example shows stress plots for one time-point points during a known excitation of the first stage. Previous analysis techniques would not have captured the coupled effects that drive stresses on the second stage. This computationally efficient approach, however, now captures the multi-stage interaction, and reveals an important first step in the development of tools to enable system-level STFs.

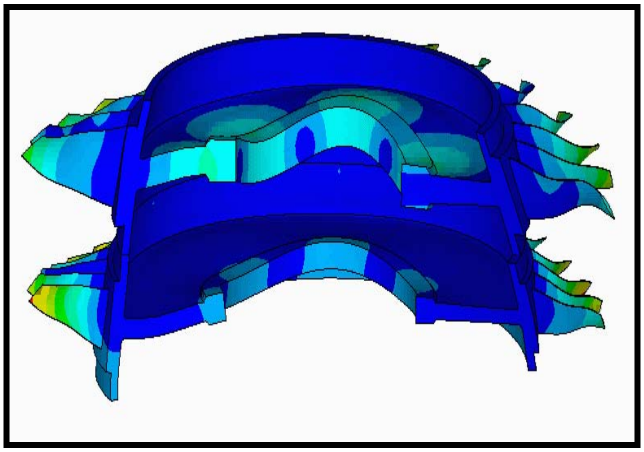

Figure 7: CMS Modeling Captures Multi-stage Interaction

COMPONENT HEALTH AND REMAINING CAPABILITY PROGNOSIS

The second critical role of a comprehensive PHM system is the projection of remaining useful service life based on present condition, prognosticated state and projected future use. On-going efforts focus on the reduction of prediction and operational uncertainty from multiple sources. Uncertainty inherent to current predictive tools drives excessive conservatism in select cases, while operational uncertainty can tend to drive both excessive conservatism for select cases and anti-conservatism for other cases. Quantitative identification of predictive and operational uncertainty will result in much higher fidelity component health consumption / usage assessments that are critical to the operational viability of comprehensive prognostic capability.

One example of excessive conservatism is in the application of current crack growth predictive tools for the development of STFs. While the current tools have been tremendously successful for providing for safe operational limits for fielded engines, their application to the development of crack growth related STFs was found to be insufficient for cracks growing in complex geometries and for larger cracks. That is, the current tools were found to provide a highly conservative measure of final crack size, and thus provide an inaccurate representation of projected remaining life vs. crack size for cracks in complex geometries, and for the case of large cracks. Advanced 3D crack growth predictive tools were demonstrated to still provide a conservative assessment of crack growth life, while providing a more accurate assessment than current tools. An example of predictions from current 2D tools, advanced 3D predictive tools, and experimental data is provided in Figure 8.

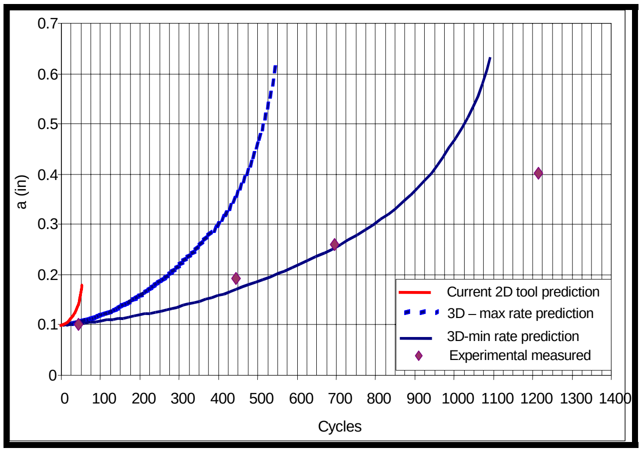

Figure 8: Comparison of Crack Growth Predictions and Spin Test Data

An additional factor contributing to the uncertainty in component remaining life predictions is the dependence of crack growth rate on the specific component processing path and resulting material microstructure. An effective comprehensive PHM system will utilize knowledge of these local variations in crack growth rate, which will be incorporated into the advanced 3D crack growth predictive tools discussed above. A recent assessment of the impact of microstructure on the fatigue crack growth life of two similar geometry Ti-6Al-4V rotor forgings demonstrated an opportunity to improve remaining life predictions by 38-65%. Similar opportunities exist in wrought nickel alloys as well as advanced powder processed materials. Further improvements in remaining life prediction and reduction in prediction conservatism will require a full understanding of the fatigue crack growth response of various material microstructures to dwell loading conditions.

SUMMARY

Advanced prognosis health management systems are under development to fully integrate next generation diagnostic techniques, component damage evolution models and multi-component system level structural analysis approaches. These disparate aspects of propulsion system health are linked through the structural transfer function (STF) approach, where location specific damage signatures are analytically defined and experimentally sensed and validated. The validity of the STF approach has been demonstrated for complex locations on both airfoil and disk components in realistic spin test environments. Advanced time-of-arrival sensors, integrated within an advanced PHM system, were shown to be capable of rotor disk LCF crack detection and prognosis of remaining life prior to disk rupture. On airfoil geometry locations, a combined approach has been outlined using transient ANSYS analysis and component mode synthesis techniques to generate STFs for specific high responding HCF modes.

ACKNOWLEDGEMENTS

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