Damage Precursor Index (DPI) Methodology for Aviation Structures

Conference Paper · July 2016

6 authors, including:

Ed Habtour
Sandia National Laboratories
61 PUBLICATIONS **270** CITATIONS
SEE PROFILE

Daniel Cole
Army Research Laboratory
47 PUBLICATIONS **511** CITATIONS
SEE PROFILE

Christopher Kube
Pennsylvania State University
52 PUBLICATIONS **188** CITATIONS
SEE PROFILE

Mark E. Robeson
US Army
26 PUBLICATIONS **64** CITATIONS
SEE PROFILE

Damage Precursor Index (DPI) Methodology for Aviation Structures

Ed Habtour[1], Daniel Cole[1], Christopher Kube[1], Adam Svensken[1], Mark Robeson[2], and Abhijit Dasgupta[3]

[1] Vehicle Technology Directorate U. S. Army Research Laboratory, APG, MD 21005 USA

[2]Aviation Development Directorate – Aviation Applied Technology Directorate, U. S. Army Aviation and Missile Research, Development, and Engineering Center, Ft. Eustis, VA 23604 USA

[3]Center for Advanced Life Cycle Engineering, University of Maryland, MD 20742 USA

Abstract

In this study, a Damage Precursor Index (DPI) methodology is proposed to track the evolution of fatigue damage precursors immediately after establishing the dynamic behavior of a structure. The DPI is used to measure the change in the state of fatigue damage precursors in structures exposed to vibration loads. The DPI is based on estimating the nonlinear dynamic parameters in isotropic materials prior to crack formation. The model accounts for the incubation and evolution of localized material microplasticity. Structural compliance due to the presence of the micro-plasticity is observed experimentally. The change in the dynamic response as a result of damage precursors is used to update the global dynamic parameters, which are used to calculate a corresponding DPI. The fatigue damage precursors are verified through series of macro/micromechanical characterizations of isotropic structures under vibration loads. The application of the DPI methodology to structural health monitoring systems may considerably improve health awareness in complex systems due to the addition of sensitivity to damage precursors.

Keywords: Damage precursor, fatigue, monitoring, nonlinear, micromechanics

1. INTRODUCTION

There is no single structural health monitoring (SHM) or prognostic health management (PHM) method today capable of performing on board near-real-time health assessment of rotorcrafts. This deficiency is related to both intrinsic and extrinsic factors. The intrinsic factors may consist of limitations in the SHM and PHM hardware and software, and uncertainties in measurable parameters. The extrinsic factors may include variability in the operational conditions, complexity of components (varying geometries and materials), and synchronous activation of multiple damage mechanisms. Therefore, describing the evolution in the material state is extremely challenging due to these factors. Subsequently, the key barrier to efficiently develop and implement prognostics and diagnostics hardware and software is our limited understanding of precursors to failure [1, 2]. Currently in helicopters, there is inadequate knowledge as to what component should be instrumented, how the signal is collected, and how to process the data to reliably predict the remaining useful life (RUL). Currently, the safety of Army rotorcraft structures relies on None-Destructive evaluation (NDE) techniques intended to detect flaws and cracks. NDE inspections are routinely carried out to evaluate the integrity of critical components. Since fatigue-critical components require scheduled inspections during their lifetime, the NDE inspections can be expensive, and time-consuming.

It is well understood that the design and maintenance of helicopters are arguably more complex compared to fixed-wing aircraft. There three aspects to these complexities, which are: 1) the flight spectrum, 2) the high velocity impact damage due to harsh environmental conditions, and 3) the inherent dynamic nonlinearities associated with the vehicle itself. It is important to point out that the flight dynamic spectrum is typically composed of a low number of high-amplitude cycles due to mechanical rotation coupled with high number of low-amplitude random vibrations due to fluid–structure interactions as well as interactions between various static and dynamic components. The extrinsic and intrinsic factors coupled with the platform design and maintenance complexities underscore the importance and difficulty of SHM/PHM techniques for monitoring the health of critical components in aviation platforms. Therefore, engineers apply two classical approaches to compensate for these challenges: 1) introduce multiple safety and correction factors, and 2) collect massive amount of data to trace failures and to guide corrective designs. In this paper, we are advocating an overhaul of SHM by completely abandoning these classical approaches, which have been proven to be unsustainable and inaccurate. To illustrate our point we provide an example for each approach. Using safety and correction factors to mitigate fatigue in a driveshaft, classical machine design handbooks recommend applying the maximum shear [3]. The approach to size the shaft diameter, d, according to Shigley is [3]:

$$\frac{\pi d^3}{32} = n\left[\left(\frac{M_m}{S_y} + \frac{K_f M_a}{S_e}\right)^2 + \left(\frac{T_m}{S_y} + \frac{K_{fs} T_a}{S_e}\right)^2\right]^{\frac{1}{2}} \tag{1}$$

where, the safety factor is n, and the alternating and mean moments are M_a, and M_m, respectivly. The alternating and mean torques are T_a, and T_m, respectivly. The yield strength is S_y, and the fatigue strength and shear strength reduction factors are K_f, and K_{fs}, respectively. The fatigue limit, $S_e = k_a k_c k_b k_d k_e S_e'$, contains five correction factors and an additional fatigue limit, S_e'. These factors are:

k_a = Surface factor $= a\, S_{ut}^b$ (a and b are material constants, and S_{ut} is the ultimate tensile limit)

k_c = Load factor

k_b = Size factor

k_d = Temperature factor

k_e = Miscellaneous factor

The simple driveshaft component contains a total of thirteen safety and correction factors. Consequently, including these factors for each component and subsystem in a helicopter often leads to safety multiplicative effects causing nonlinear transmission of loads and undesirable constructive and destructive stress state [4, 5]. In an aircraft, for example, the safety multiplicative effect increases the size and weight of the platform, and results in producing inaccurate RLU predictions. The data collection and storing for military vehicles, shown in Figure 1, can be a costly process with questionable outcomes. Figure 1 illustrates a linear approach was attempted by the US Army to track the health and reliability of its materiel. According to the 2011 Army Acquisition Review Report, none of these steps shown in Figure 1 are truly connected and provided no coherent description of the failures encountered in the field. The report also states that there was no realistic, or formal way to track and analyze failures from past acquisitions.

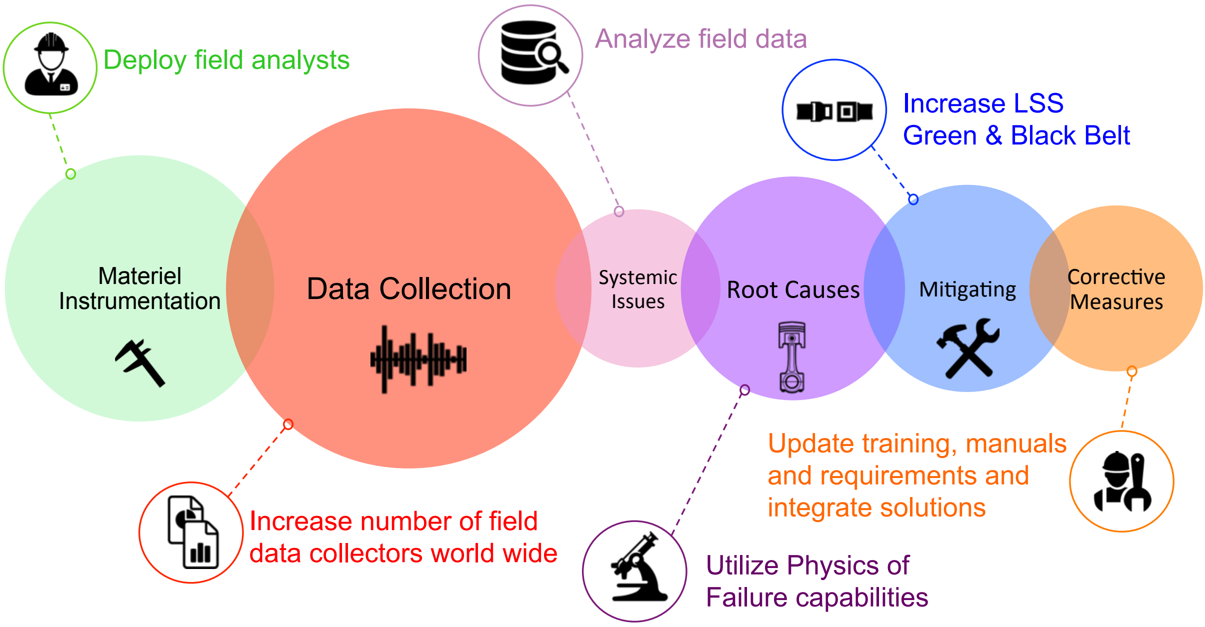

Figure 1: Linear approach to data collection in Army materiel

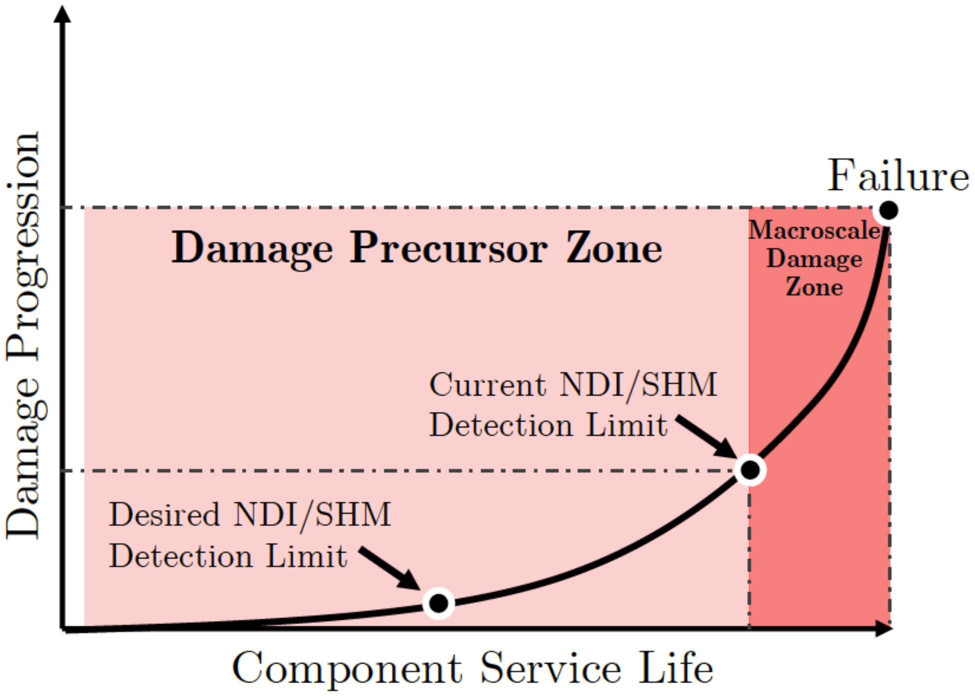

Figure 2: Precursor to fatigue damage

It is fair to say that SHM/PHM systems have demonstrated impressive capabilities in detecting, locating, and estimating the size of cracks in structures. However, in order to meet the Army's goals for fatigue-free operation, over the life of a structural component, we must galvanize a complete transformation of traditional SHM/PHM from hunting for cracks to a truly bio-inspired health state awareness by detecting precursors to fatigue damage (e.g., bruises, and pain in human system). Precursors are not necessarily independent singularities that can be measured, such as cracks of a certain length. Instead, we think of precursors as characteristics of the materials state, where the physical trends are manifestations for the health of a component during its service life. For example, we show in this paper as steel 1095 cantilever beams are exposed to nonlinear vibrations over time micro-plasticity can be detected using nonlinear dynamic parameters, prior to crack initiation. Therefore, we define *Damage Precursor* here as any observable early degradation of the material microstructural morphology and resulting changes in the physical properties of a structure, prior to any detectable crack initiation, Figure 2. Examples of measurable precursors to fatigue crack development may involve, but are not restricted to, changes in electrical signal, acoustic response, thermal signature, dislocation density, or mechanical response during service life. Thus, a Damage Precursor Index (DPI) is not a straightforward process. We claim that the DPI depends on the material type and process, loading profile, and environmental conditions.

It is important to point out that the concept of damage precursor is not new. For example in metallic structures at highly stressed regions localized dislocation motion form persistent slip bands (PSBs), which are referred to as embryonic cracks [6, 7]. Dislocation motion is a primary mechanism of plastic deformation in metals and has been shown to result in slip within the grains in polycrystalline materials [8]. The novelty of our approach is connecting three disciplines: nonlinear dynamics (global: macroscale), structural mechanics (global and mesoscale) and micromechanics (micro/nano-scale), as shown in Figure 3. We were able to observe changes in microstructural properties by tracking changes in the nonlinear dynamic response of a cantilever beam exposed to nonlinear vibration. The nonlinear vibration-based method appeared to be an attractive and simple global approach for monitoring the changes in the structural dynamic characteristics due to the evolution in the microstructure. However, the focus of the paper is on the DPI development based on the global structural response.

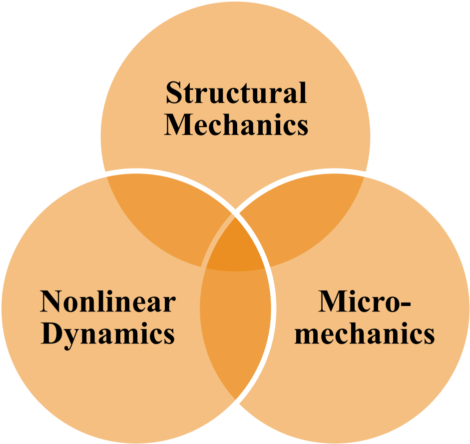

Figure 3: Multidisciplinary approach to establish a Damage Precursor Indicator (DPI)

2. EXPERIMENTAL APPROACH

Objective of the study is to incorporate precursor into a nonlinear global structural dynamic model. The nonlinear parameters in the equation of motion can be used as a DPI. The model is based on the dynamic response of slender isotropy cantilever beams made of blue-finished, polished, spring-tempered AISI 1095 high-carbon steel. The density and the elastic modulus of the material are 7.85 g/cm^3, and 205 GPa, respectively. The beam length and cross-section area are 127mm and 15.88×1.08 mm^2, respectively. The beam is clamped to a rigid fixture as shown in Figure 4-a, where the fixture is attached to a shaker as shown in Figure 4-b.

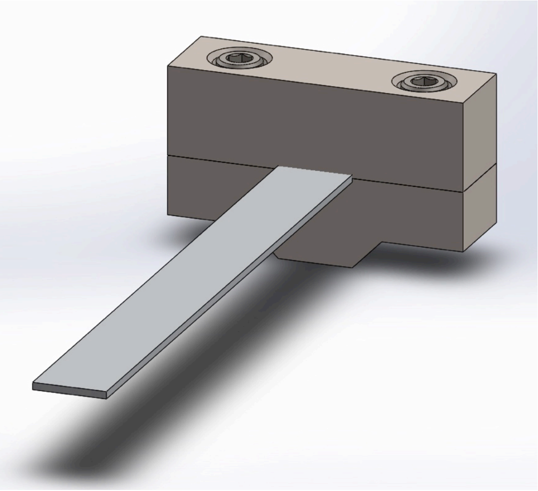

Figure 4: (a) beam with fixture

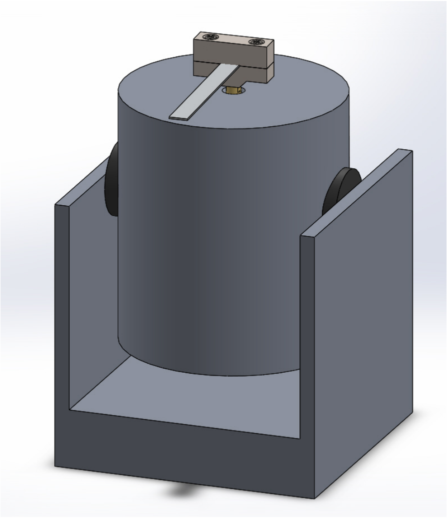

Figure 4: (b) fixture attached to the shaker

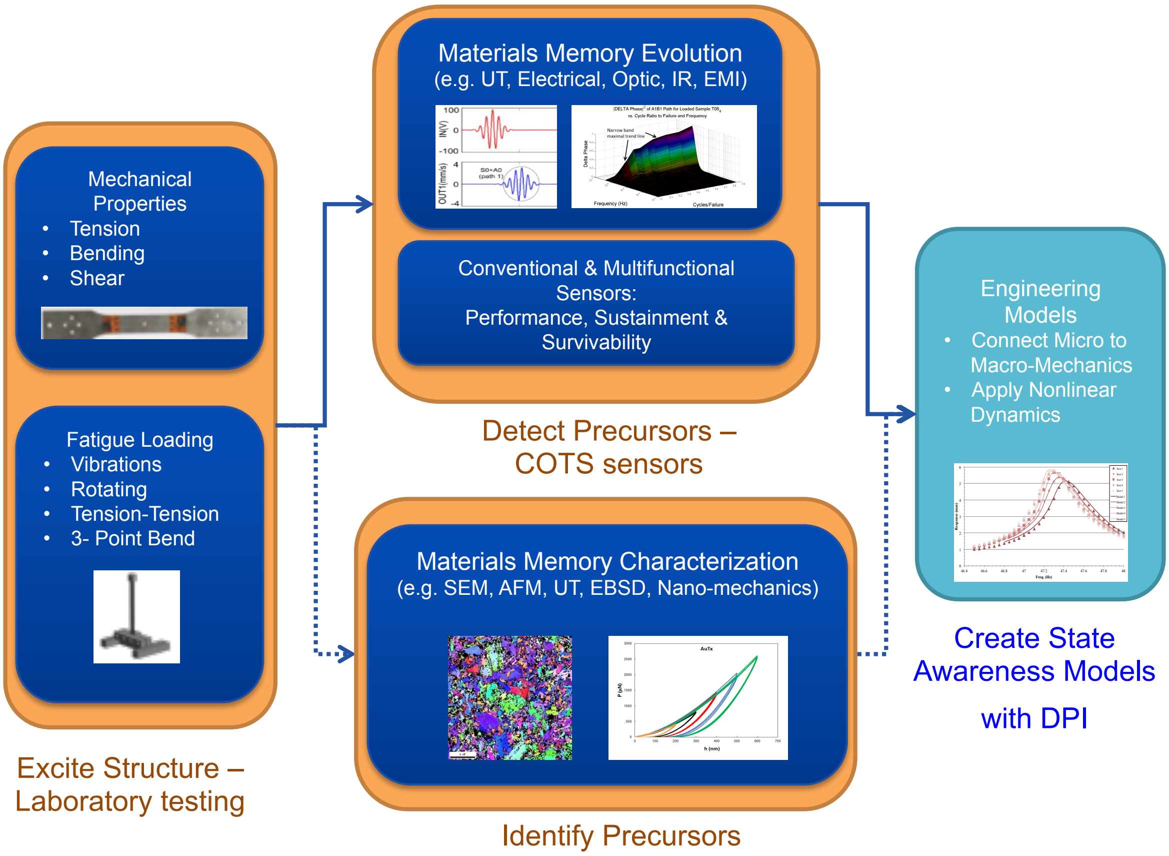

Figure 5: Methodology for connecting micro- to meso- to macro-mechanics and establishing a Damage Precursor Indicator (DPI)

The process of the experimental approach and the theoretical model is shown in Figure 5. A series of experiments were performed to establish baseline properties of the materials per

ASTM standards. The experiments consisted of monotonic tension tests to understand the structural characteristics of such materials followed by vibration tests. Two sets of experiments were conducted with 0.1 and 0.3 g vibration base excitation. Once the linear fundamental frequency for each beam was identified using sine-sweep excitation, the beams were exposed to the transverse harmonic base excitation at discrete forward dwell frequencies near the fundamental frequencies. The ramp-up time and dwell time for each frequency were 30s and 25s, respectively, where frequency step for each dwell was 0.05 Hz. Therefore, the excitation frequency was increased 0.05 Hz every 55s (30s ramp-up plus 25s dwell). It should be noted that the stresses during oscillation were kept well below the endurance limit (within the infinite life region). While the bulk mechanical properties did not vary as a result of the oscillations, the local properties varied significantly and were correlated to the global dynamic behavior through COTS (Commercial off the Shelf) accelerometers and strain gages.

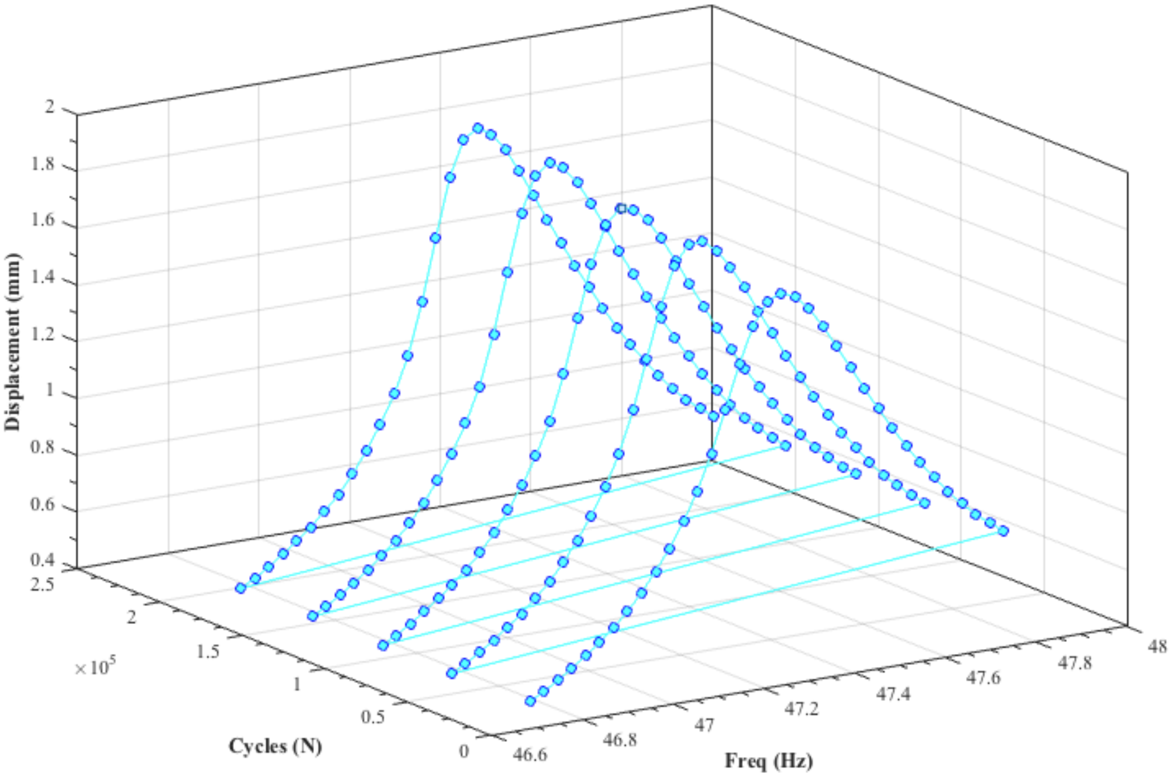

Figure 6: Beam's tip response as a function of excitation frequency and loading cycles due to 0.1 g base harmonic excitation, markers: experiments, and solid lines: model

In the context of fatigue damage, precursors to fatigue crack nucleation appeared as a change in the elastic modulus of the beam surface, which was manifested in the nonlinear structural response shown in the experimental and analytical results for 0.1 and 0.3 g in Figures 6 and 7, respectively. Both figures show that precursors appeared to increase the beam tip deflection and drop the nonlinear resonance as a function of loading cycles.

The micromechanics analysis was necessary to understand the interaction between the various constituents within the materials system. Such a micromechanical evaluation provided insights into evaluating the evolution in the microstructure up to the creation of embryonic cracks. The variation in micro- and meso-scale material properties informed an analytical model based on a DPI using nonlinear parameters estimation technique.

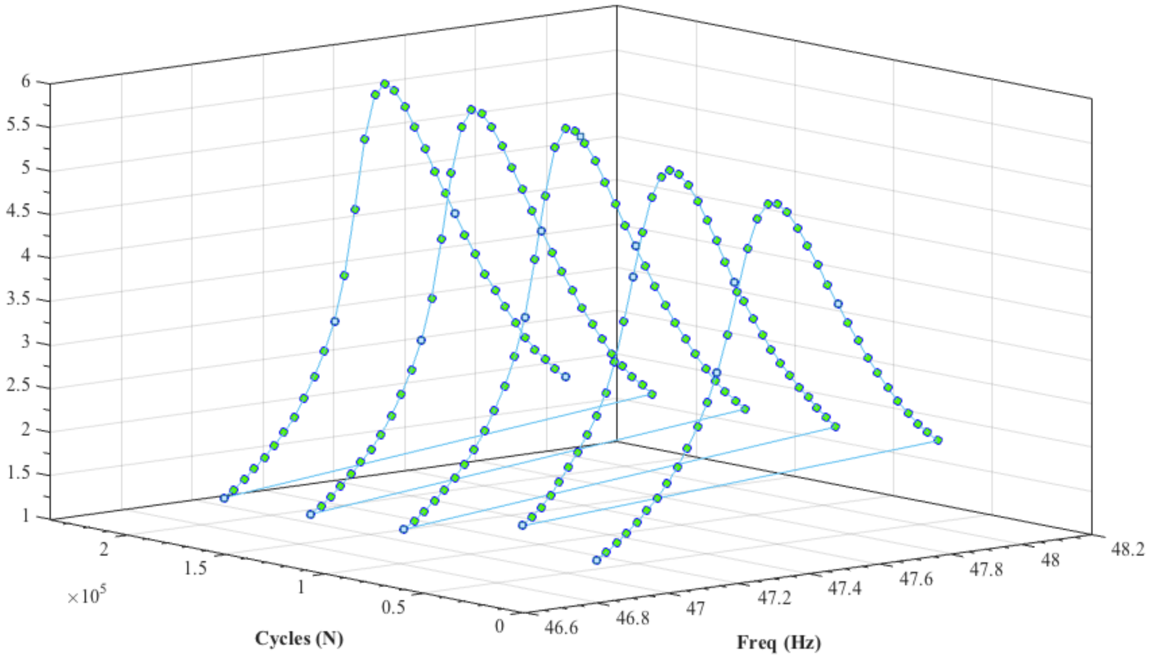

Figure 7: Beam's tip response as a function of excitation frequency and loading cycles due to 0.3 g base harmonic excitation, markers: experiments, and solid lines: model

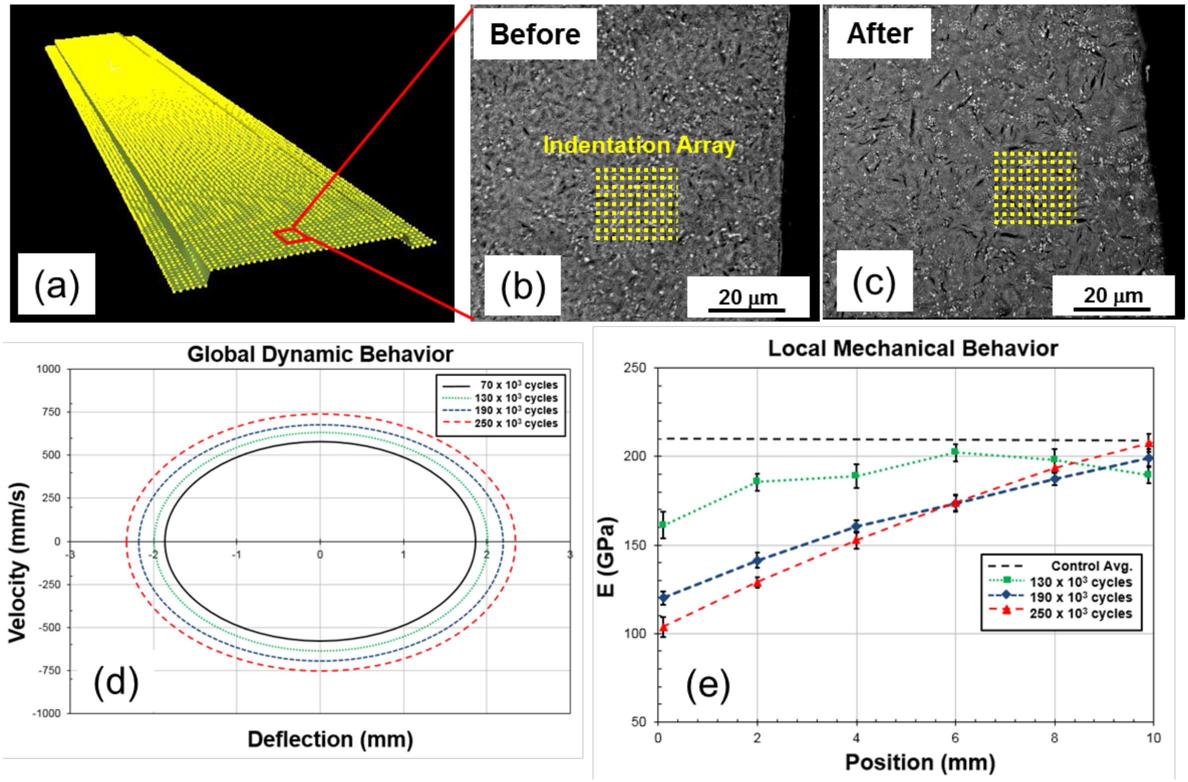

Figure 8: (a) beam profile exposed to nonlinear oscillation; microstructure (b) before and (c) after fatigue; (d) global dynamic response at various loading cycles; (e) local stiffness of beam surface near root using nanoindentation [1]

Recently, we have shown experimentally a link between the global dynamic behavior and mechanical properties of a slender alloy beam (Figure 8) subjected to nonlinear harmonic oscillation [1]. The dynamic response corresponded to variation in the material properties (Figure 6-c). The global behavior of the beam during oscillation was analyzed in terms of beam tip velocity versus tip displacement for 70 x 10^3, 130 x 10^3, 190 x 10^3, and 250 x 10^3 cycles [9]. An increase in the tip velocity/displacement was observed as a function of increasing number of loading cycles (Figure 6-d). Nanoindentation tests were performed on the fatigued structures, targeting various positions along the beam's long axis. A clear variation in the local compliance was observed for indentations approaching the beam root (Figure 6-e).

3. MODELING APPROACH AND RESULTS DISCUSSION

The aim of the engineering modeling task in Figure 5 was to track the evolution of a fatigue damage precursor of structures exposed to vibratory loads by exploiting the interplay between micromechanics and nonlinear dynamic parameters. The analytical model was based on nonlinear Euler-Bernoulli beam theory, which included the nonlinear inertial and nonlinear geometric terms. The model continually re-estimated the dynamic response based on fatigue damage accumulation. The nonlinear changes in the material and kinematic stiffness (geometric nonlinearity) necessitated the following steps: a) obtaining the viscous damping for each experiment, b) updating the nonlinear inertial terms, c) attaining both the linear structural stiffness and nonlinear geometric stiffness from experiments and parameters sensitivity optimization analysis. This approach is needed because the material and geometric nonlinearities are contained in the dynamic model parameters. The equation of motion for the nonlinear system is [1]:

$$m_{eff}\ddot{x} + 2\zeta m_{eff}\omega_n\dot{x} + k_{eff}x + N_{iner}(x^2\ddot{x} + x\dot{x}^2) + N_{geom}x^3 = F_o\cos(\omega_{ex}t) \tag{2}$$

The dot superscript denotes the time, *t*, derivative and *x* is the displacement. The effective mass including the rotary inertia is m_{eff}. The structure damping coefficient and linear structural stiffness are ζ and k_{eff}, respectively. The fundamental frequency and forcing frequencies are ω_n and ω_{ex}, respectively. The nonlinear inertial coefficient including the tip rotary inertias is N_{iner}. The cubic spring constant, or Duffing parameter, is N_{geom}. The structural stiffness can be expressed in terms of the effective mass and fundamental frequency, as follows:

$$k_{eff} = m_{eff}\omega_n^2 \tag{3}$$

The next step is to apply the method of averaging to equation of motion [10]. Therefore, the displacement can be expressed as follows:

$$x = A(t)\cos(\omega_{ex}t + \phi) \tag{4}$$

or:

$$x = A\cos\gamma \tag{5}$$

where A is the deflection amplitude, ω_{ex} is the excitation frequency and ϕ is the phase shift. The displacement first time derivative can be expressed as follows:

$$\dot{x} = -A\Omega \sin\gamma + \dot{A}\cos\gamma - \dot{\phi}A\sin\gamma$$

The first derivative is then reduced to:

$$\dot{x} = -A\omega_{ex}\sin\gamma \tag{6}$$

The displacement second derivative becomes:

$$\ddot{x} = -A\omega_{ex}^2\cos\gamma - \dot{A}\omega_{ex}\sin\gamma - \dot{\phi}A\omega_{ex}\cos\gamma \tag{7}$$

Substituting equations (5), (6), and (7) into the equation of motion (2) and rearranging yield the following:

$$\Omega^2 = \frac{\omega_{ex}^2}{\omega_n^2} = \frac{1 + \frac{3\bar{A}^2}{4}\frac{N_{geom}}{k_{eff}}}{1 + \frac{\bar{A}^2}{2}\frac{N_{iner}}{m_{eff}}} \tag{8}$$

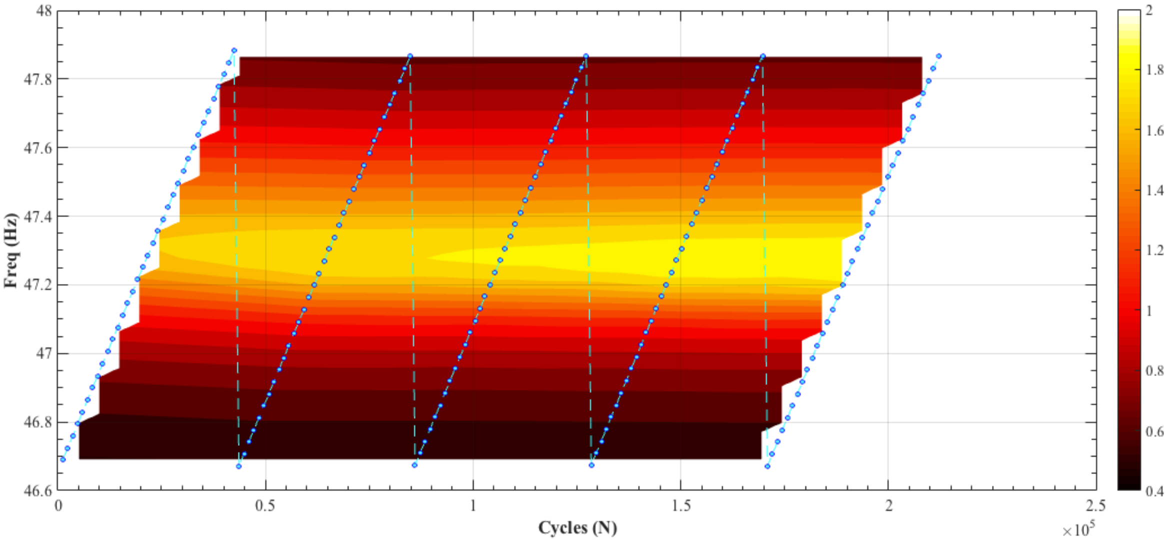

Figure 9: Equivalent nonlinear dynamic model using estimated parameters for 0.1 g excitation; excitation; markers: experiments, contour: model

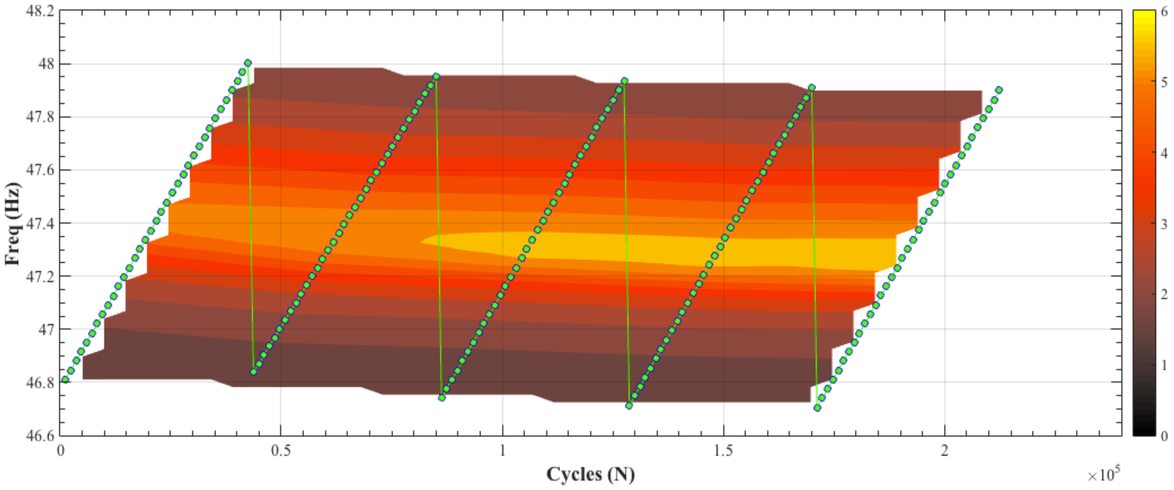

Figure 10: Equivalent nonlinear dynamic model using estimated parameters for 0.3 g excitation; markers: experiments, contour: model

The equation above estimates the shift in the nonlinear resonance frequency, Ω, due to the evolution in the material properties, where $\bar{A}$ is a normalized beam tip displacement. Accounting for changes in the local material stiffness as a function of the excitation level and number of fatigue cycles provided reasonably accurate estimate of structural displacement, as shown in Figures 6 and 7. The model was formulated to estimate the structural response based in material degradation. A map was constructed for each case (0.1 and 0.3 g) based on the estimated nonlinear parameters to predict the changes in the structural response and nonlinear resonance as a function of cycles, shown in Figures 9 and 10.

4. CONCLUSION

The effect of aging on the macroscopic dynamic response confirmed that the nonlinear parameters are viable indicators of the overall health of the system. Specifically, the present study showed that linear vibration approaches are inherently less sensitive than nonlinear vibration approaches to fatigue degradation features prior to crack initiation. The nonlinear vibration approach can be used to detect early changes in the linear and nonlinear stiffness, even prior to crack development. The power of the DPI approach is the consciousness that the incubation of damage embryos can be identified in the elastic regime, which was verified experimentally using macro/micromechanics testing.

REFERENCES

[1] Habtour, E., D. Cole, V. Weiss, M. Robeson, R. Sridharan, and A. Dasgupta. “Detection of Fatigue Damage Precursor Using a Nonlinear Vibration Approach.” *Structural Control and Health Monitoring* (2016) DOI: 10.1002/stc.1844.
[2] Lee, A., E. Habtour, and S. A. Gadsden. “Proposed Health State Awareness of Helicopter Blades using an Artificial Neural Network Strategy.” *SPIE Commercial and Scientific Sensing and Imaging* (2016).
[3] Shigley, J. E., and C. R. Mischke. *Mechanical Engineering Design*. Boston: McGraw-Hill, 2001.
[4] Carpinteri A., A. Spagnoli, and S. Vantadori. “Reformulation in the Frequency Domain of a Critical Plane-Based Multiaxial Fatigue Criterion”. *International Journal of Fatigue* (2014) DOI: 10.1016/j.ijfatigue.2014.01.008.
[5] Ernst, M., E. Habtour, A. Dasgupta, M. Pohland, M. Robeson, and M. Paulus. "Comparison of Electronic Component Durability under Uniaxial and Multiaxial Random Vibrations." *Journal of Electronics Packaging* 137.1 (2015): *DOI: 10.1115/1.4028516.*
[6] Mura, T. *Micromechanics of Defects in Solids*. The Hague: Nijhoff, 1982.
[7] Klesnil, M., and P. Lukáš. Fatigue of Metallic Materials. Amsterdam: Elsevier, 1992.
[8] Sangid, M. D. "The Physics of Fatigue Crack Initiation." *International Journal of Fatigue* 57 (2013): 58-72.
[9] Cole, D. P., and E. Habtour. “Improved Understanding of Damage Precursors Through Local Mechanical Characterization.” *ASME 2015 Conference on Smart Materials, Adaptive Structures and Intelligent Systems* (2015).
[10] Nayfeh, A. H. and D. T. Mook, *Nonlinear Oscillations,* Wiley-VCH, New York, 1995.