Utilizing Force-State Mapping for Detecting Fatigue Damage Precursors in Aerospace Applications

Ed Habtour[1,2,3], Axel Homborg[1], Dario Di Maio[3], Robert Haynes[2], Tiedo Tinga[1,3]
[1] The Netherlands Defence Academy, Den Helder, NL
[2]US Army Research Laboratory, MD, US
[3] University of Twente, Enschede, NL

The Masri-Caughey method is utilized to identify and monitor precursors to fatigue damage in aerospace alloy structures exposed to vibratory loads. The method is created originally to detect nonlinearity in a dynamical system via a direct non-parametric identification. In this paper, Force-State-Mapping (FSM) is constructed at various stages of the fatigue-life using the Masri-Caughey method. The experimental results show that FSM is a sensitive indicator for monitoring the health state of a structure prior to the development of cracks. The required restoring force due to fatiguing is obtained as a function of the vibration cycles and input loads. FSM appears to be a promising method in connecting the global structural dynamic response to the evolution in the micro-behavior of the materials due to fatigue degradation. For aerospace applications, the objective of this effort is to estimate the required restoring force using current structural health monitoring systems and supply this value to the control laws of an aircraft. Thus, an aircraft can prevent or slow crack development by autonomously readjusting its maneuver based on its health-state.

Keywords: Fatigue Damage Precursors, Structural Health Monitoring, Physics of Failures, Nonlinear Vibrations

1.0 Introduction

It is well known that the design and maintenance of military helicopters are far more complex than a fixed-wing aircraft[1]. The flight spectrum, and inherent dynamic nonlinearities associated with the helicopter itself exacerbate the maintenance complexity and cost. The flight spectrum is typically composed of high-amplitude cycles due to mechanical rotations in multiple subsystems, and low-amplitude high frequency random vibrations due to fluid-structure interactions[1]. Over the past 20 years, monitoring systems have been introduced in rotorcrafts to improve safety, and reduce maintenance cost as Health and Usage Monitoring System (HUMS), Structural Health Monitoring (SHM), and Prognostic Health Management (PHM)[2].

Several research studies have demonstrated significant improvements in increasing the damage detection sensitivity in aircraft health monitoring in laboratory environments[2]. Transitioning improvements found in laboratories to fielded systems has proven to be difficult due to intrinsic and extrinsic factors[1]. In military rotorcrafts, the intrinsic factors may consist of mechanical interactions between components, or uncertainties in sensory measurements due to software and hardware limitations. The extrinsic factors can be aggressive operations, and variabilities to various environmental conditions. Any combination of these factors can lead to synchronized activations of multiple failure modes[1]. Additionally, aviation weight, and cost restrictions worsen the transitioning opportunities. Thus, describing the evolution in the health-states of helicopters, for example, can be extremely challenging.

Force State Mapping (FSM) has been proposed in this paper as a methodology to assess the health-state of such complex systems. FSM is a well know nonlinear identification method (NIM), which can be utilized to estimate the stiffness and damping properties of a nonlinear structure developed by Masri and Caughey[3]. They created this method mainly to detect nonlinearity in a structural system. There are various NIMs available in the literature such as such as Hilbert and wavelet transforms, reverse path method, and nonlinear subspace identification[4,5]. However, FSM is an attractive approach because it has been successfully applied to various aeronautical structures to experimentally detect weak nonlinear softening in helicopters and airplane[6]. Noël and Kerschen provided an excellent review on the latest developments in NIMs[5].

The preliminary results in this study indicate that FSM can be utilized to amplify the sensitive of health monitoring systems to detect precursors to fatigue damage. The concept was demonstrated using a beam-like aluminum 7075-T6 structure, which was exposed to random vibration fatigue. Undamaged state system parameters were extracted to establish a baseline set, which was utilized to track changes in these parameters over the life-cycle of the strcutre. Previous studies have shown connections between changes in the nonlinear dynamic parameters and fatigue damage precursors (DP)[7]. DP is defined as any observable early degradation in the material microstructural morphology, and mechanical properties prior to detectable fatigue crack[8,9]. Examples of DPs are changes in the materials grain size, dislocation density, electrical impedance, or acoustic signature[7-9].

2.0 Experimental Approach:

Cantilevered aluminum 7075-T6 beams were exposed to narrowband random vibration fatigue. The beams dimensions were 125.0×12.0×1.64 mm^3. Each beam was rigidly clammed to a hardened steel fixture, where 11 N-m torque was applied to each bolt. Data Physics shaker and controller (model No. V400LT and 901, respectively) were utilized to perform the vibration characterization and fatigue. Accelerometers PCB 352A24 and PCB 352A21 were attached to the clamp-fixture, and the beam tip, respectively. The shaker was controlled using the fixture's accelerometer. For each vibration fatigue test, a characterization pause was required every 15 minutes to extract the linear and nonlinear parameters required for assessing to health-state. The characterization pauses consisted of wideband (10-1000 Hz) low-amplitude (0.0025 g^2/Hz) random base excitation, and 1 G amplitude forward-backward sine sweeps at 0.075 Hz/s. The procedure for extracting the linear and nonlinear parameters are detailed in Section 4.0. Each time the test was paused, the bolt tightness was checked with a torque wrench to eliminate potential change in damping coefficient. The fatigue test was performed by inducing narrowband random vibration profile with frequency range of ~ $f_n \pm 2.5$ Hz, where f_n is the natural frequency of the beam. Complete fracture occurred approximately $\sim 10^6$cycles.

3.0 Nonlinear Identification Approach:

To track the health-state of structures exposed to vibratory loads, monitoring the change in the FSM, and the nonlinear geometric stiffness coefficient, k_n, are the primary focus. Applying high amplitude sine-sweep base excitation at low frequency rate is advantageous because it amplifies the nonlinear parameters, which are sensitive to the development of precursors to fatigue. Thus, it is possible to monitor changes in these parameters as fatigue builds up. The equation of motion for a beam-like system can be expressed as follows[10]:

$$m_s\,\ddot{x} + 2\zeta m_s \omega_n \dot{x} + k_l x + m_n(x^2\ddot{x} + x\dot{x}^2) + k_n x^3 = F\cos\,(\omega_f t) \tag{1}$$

The dots superscripts represent the temporal derivatives of the beam tip displacement, x. The structure distributive mass, and its nonlinear inertia are m_s and m_n, respectively. The fundamental, and excitation frequencies are ω_n and ω, respectively. The structural damping ratio, and linear stiffness are ζ and k_l, respectively. The coefficient k_n is also referred to as the cubic spring constant, or Duffing parameter. The mathematical expressions for the coefficients in the equation of motions are detailed in[10]. F is the maximum input magnitude for the forcing function. The structural stiffness can be expressed in terms of m_s and ω_n, as follows:

$$k_l = m_s \omega_n^2 \tag{2}$$

The equation of motion is conveniently expressed in terms of forces normalized by the beam distributive mass as follows:

$$\ddot{x} + \mu\dot{x} + \omega_n^2 x + n_i(x^2\ddot{x} + x\dot{x}^2) + n_g\,x^3 = F_b(t) \tag{3}$$

where, the coefficients μ, n_i, and n_g are the damping, nonlinear inertia, and geometric stiffness normalized by the mass, respectively. Since we are interested in the first mode of the beam, n_i can be neglected because it is low for the first mode[7,10]. The base excitation normalized by the mass is F_b.

The nonlinear system identification is accomplished by equating the dynamic force to the internal restoring force that returns the system back to equilibrium state. The dynamic force consists of the terms containing accelerations, namely base excitation and inertial response. The restoring force is FSM, which is a function of displacement and velocity. Thus,

$$FSM = \mu\dot{x} + \omega_n^2 x + n_g\,x^3 = F_b - \ddot{x} \tag{3}$$

The Inertial acceleration, and base excitation can be obtained from experimental measurements. The displacement and velocity are calculated via numerical integration of acceleration measurements. The damping ratio can be estimated using various methods such as half-power bandwidth, and logarithmic decrement. The geometric stiffness is calculated as follows:

$$n_g = \frac{FSM - \mu\dot{x} - \omega_n^2 x}{x^3} \tag{4}$$

The system health-state monitoring is achieved by estimating FSM_o, and n_{go} for the undamaged state to establish a baseline set then checking the changes in these parameters over the life-cycle of the system. The damage evolution is estimated by comparing FSM_o, and n_{go} to the subsequent FSM, and n_g values after periodic operations.

4.0 Results

Estimating changes in FSM, and n_g necessitates the following steps: (1) assessing damping, (2) extracting natural frequency, and (3) calculating the linear and nonlinear stiffness coefficients after each experiment. Linear and nonlinear parameters were obtained every ~15 minutes exposure to vibration fatigue from frequency response plots of the beam tip acceleration response due to random and sine-sweep excitations, respectively. For a pristine beam the fundamental frequencies in the linear or nonlinear dynamic regime were approximately 66.5 and 68.4 Hz, respectively. The half-power bandwidth method was utilized to estimate the damping ratio, where the amplitude of interest is $\ddot{x}_{max}/\sqrt{2}$, as follows:

$$2\zeta = \frac{\omega_2 - \omega_1}{\omega_n} \tag{5}$$

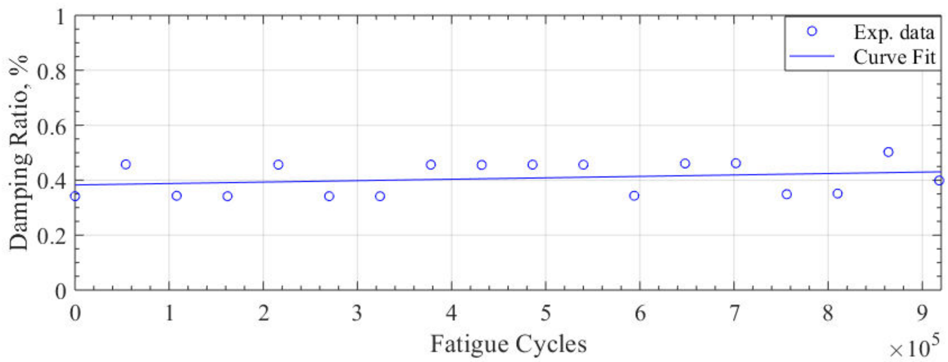

Figure 1 Damping ratio estimate using half-power bandwidth as a function of fatigue cycles

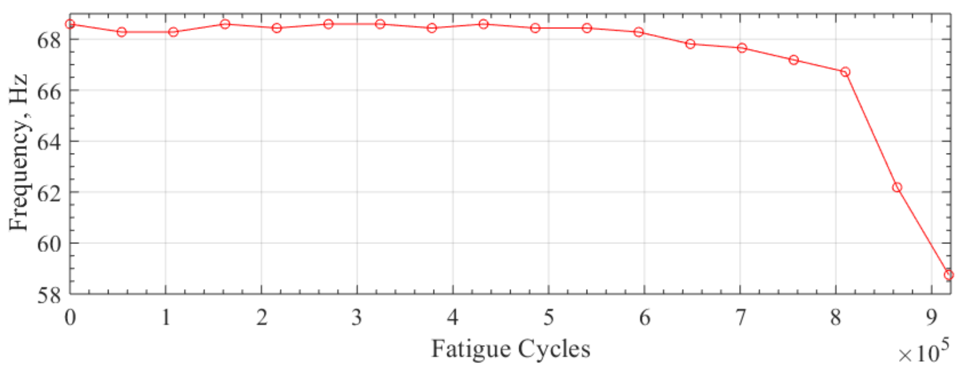

Figure 2 Shift in the natural frequency as a function of fatigue cycles

The change in the damping ratio was almost unchanged as a function of fatigue cycles, as shown in Figure 1. The shift in the natural frequency remained insignificant until the beam exceeded ~75% of fatigue cycles, as shown in Figure 2. The natural frequency shift became sensitive to damage only when the beam remaining useful life was less than 25%. Thus, monitoring the shift in the natural frequency was an unreliable damage indicator since its sensitivity to fatigue damage precursors was low. For completeness, the full acceleration response spectrum for the entire fatigue tests is provided in Figure 3.

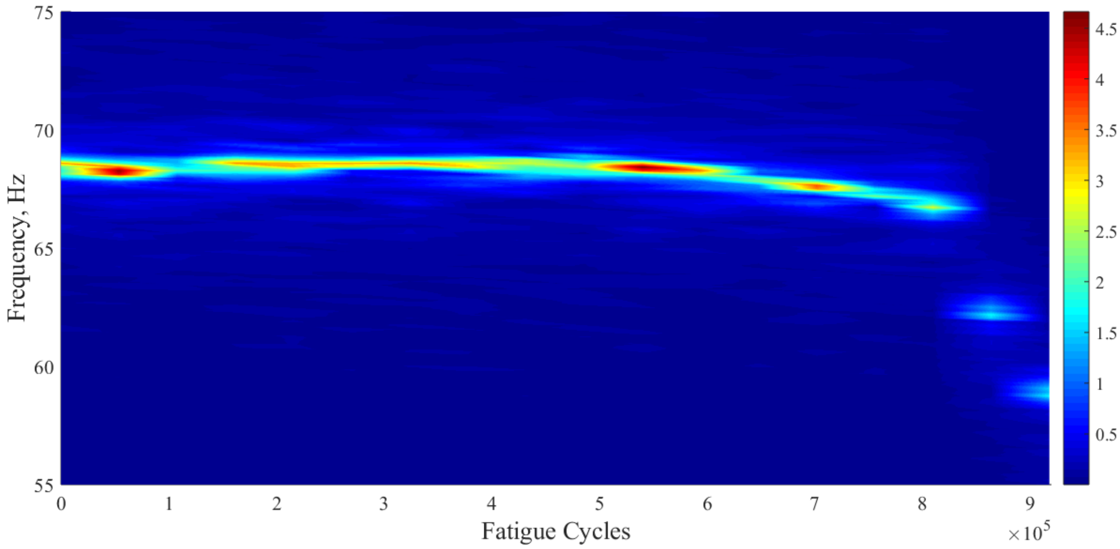

Figure 3 Beam tip acceleration response spectrum in Gs due to exposure to vibration fatigue

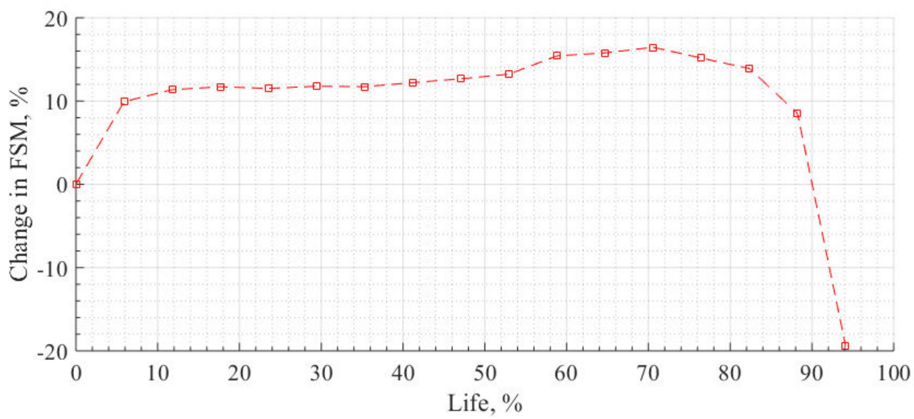

Figure 4 Rate of change in FSM throughout the life of the beam

Forward and backward low rate sine-sweep vibration tests were utilized to calculate the change in FSM as a function of fatigue cycles, as shown in Figure 4. The change in FSM due to fatigue appeared to be far more significant that rate of change in the natural frequency, especially at the early stage of life. Overall, the change in FSM was relatively graceful until 85% of life was consumed. As shown in Figure 4, during the first ~20% of fatigue life, FSM changed by approximately 12% then remained unchanged up to 35% of life. The changed in FSM continued to increase up to 70% of life, after which it started to decrease. The drastic drop in FSM could be an indication of crack development in the structure. The initial asymptotic increase and secondary increase could be due to materials softening-hardening phase transformation. In a separate study, Haynes et al. has shown that Al 7075-T6 structures under random vibration fatigue could experience structural hardening in the first 25% of fatigue life, followed by softening then hardening up to 50% and 75% of fatigue life, respectively[11].

The change in the nonlinear geometric stiffness were calculated using Eq. (4). In Figure 5, the change in the nonlinear stiffness parameter relative to the baseline state is plotted as a function of the fatigue life. In general, n_g/n_{go} appeared to be more sensitive to DP than tracking the change in the natural frequency. The sensitivity of the nonlinear ratio increased drastically after 40% of the fatigue life.

It is important to point out the results in this investigation are still in the preliminary stage. The next research phase is to investigate the cause of the amplify sensitivity of: (1) FSM at the early stage of fatigue, and (2) n_g starting at 40% of life. To this end, a potential path forward after replicating the results for different structures, is to investigate the possibility of combining FSM, and n_g into one indicator.

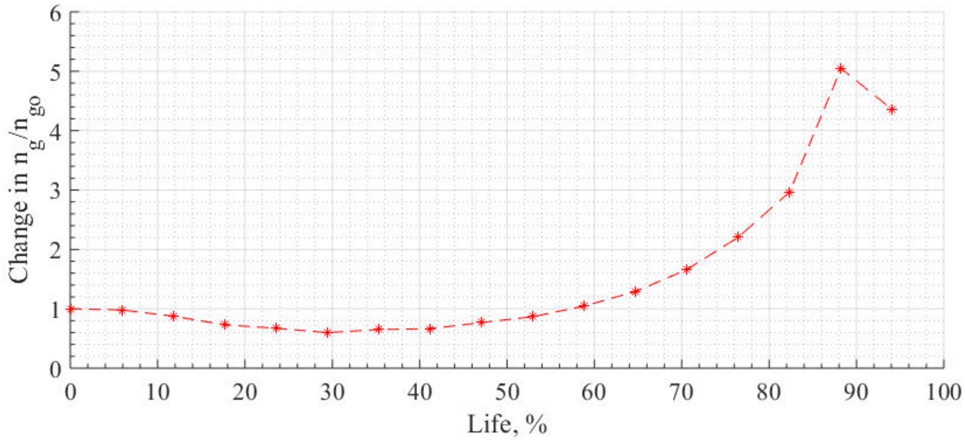

Figure 5 Rate of change in the nonlinear geometric stiffness over the beam life

5.0 Conclusion

Tracking the changes in Force-State-Mapping and nonlinear geometric stiffness of aluminum aerospace structures show promise as sensitive indicators to precursors of fatigue damage. The interplay between the nonlinear parameters in global-state and the development of damage precursors at the micro-states was demonstrated for hinge-less blade-like beams exposed to vibration base excitation. While exploiting both the Force-State-Mapping and nonlinear parameters hold promise in enhancing the sensitivity of health monitoring methods, scalability to more realistic systems than hinge-less blade-like beams is expected to be challenging and the subject of future studies.

REFERENCES

1. Habtour, E. *et al.* Damage precursor index (DPI) methodology for aviation structures. in *8th European Workshop on Structural Health Monitoring, EWSHM 2016* **2,** (2016).
2. Holford, K. M. *et al.* A new methodology for automating acoustic emission detection of metallic fatigue fractures in highly demanding aerospace environments: An overview. *Prog. Aerosp. Sci.* **90,** 1–11 (2017).
3. Masri, S. F., Bekey, G. A., Sassi, H. & Caughey, T. K. Non□parametric identification of a class of nonlinear multidegree dynamic systems. *Earthq. Eng. Struct. Dyn.* **10,** 1–30 (1982).
4. Kerschen, G., Worden, K., Vakakis, A. F. & Golinval, J. C. Nonlinear System Identification in Structural Dynamics : Current Status and Future Directions. *25th Int. Modal Anal. Conf.* (2007).
5. Noël, J. P. & Kerschen, G. Nonlinear system identification in structural dynamics: 10 more years of progress. *Mech. Syst. Signal Process.* **83,** 2–35 (2017).
6. Carrella, A. & Ewins, D. J. Identifying and quantifying structural nonlinearities in engineering applications from measured frequency response functions. *Mech. Syst. Signal Process.* **25,** 1011–1027 (2011).
7. Cole, D. P. *et al.* Local Mechanical Behavior of Steel Exposed to Nonlinear Harmonic Oscillation. *Exp. Mech.* **57,** 1027–1035 (2017).
8. Sangid, M. D. The physics of fatigue crack initiation. *Int. J. Fatigue* **57,** 58–72 (2013).
9. Vantadori, S. *et al.* Methodology for assessing embryonic cracks development in structures under high-cycle multiaxial random vibrations. *Fatigue Fract. Eng. Mater. Struct.* **41,** 20–28 (2018).
10. Habtour, E. *et al.* Detection of fatigue damage precursor using a nonlinear vibration approach. *Struct. Control Heal. Monit.* (2016). doi:10.1002/stc.1844
11. Haynes, R. *et al.* Damage Precursor Indicator for Aluminum 7075-T6 Based on Nonlinear Dynamics. *SEM IMAC-XXXVI* (2016).