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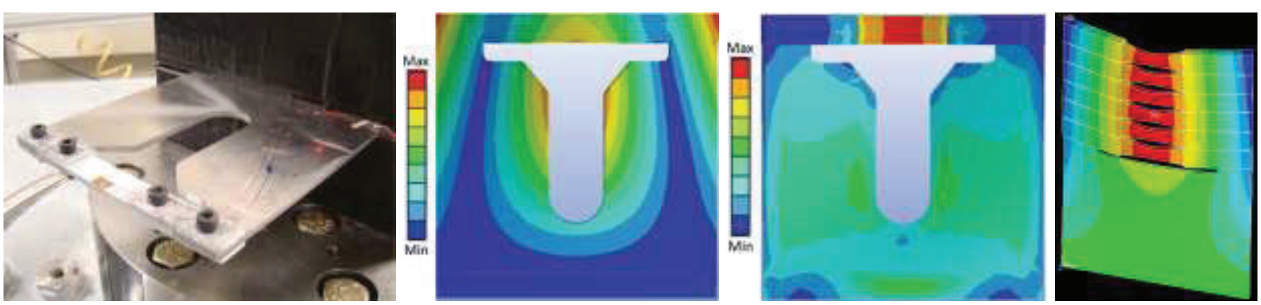
A Voltage Drop Criterion for Identifying Failed Specimens in High-Throughput Fatigue Experiments

The objective of this proposed research is to enable an improved, high-throughput measurement technique for studying very high cycle fatigue (VHCF) which can also be applied to high temperature settings.

Significance of Research

In current and next-generation gas turbine engines, structural components are subjected to extreme temperatures and vibratory loads. Combined thermo-acoustic environments ultimately lead to high-cycle fatigue, which limits the life of the engine. Thus, to ensure the performance, safety, and reliability of the engine, components must be designed using materials which have been characterized to withstand high cycle thermo-acoustic fatigue under relevant operating conditions. However, high cycle fatigue experiments can be costly and time-consuming; A single axial fatigue test operating at 40 Hz requires almost 70 hours to accumulate enough cycles (on the order of 10^7) to generate a single point on an S-N Curve. Additionally, due to statistical variability in fatigue measurements, such tests must often be repeated multiple times for a given set of operating conditions. Thus, it is desirable to develop other high cycle fatigue experiments that are more cost and time efficient.

A favorable alternative to axial testing is vibration-based methods, which are performed at higher frequencies and can accumulate specimen fatigue more quickly. Additionally, vibration-based methods better reproduce the operating environment of the engine. The Air Force Research Lab (AFRL) current uses a technique in which a square plate carries a single beam-like specimen as shown in Figure 1(a). The plate is clamped along the edge opposite the specimen and excited to its 4th resonant mode by a mechanical shaker, resulting in a uniaxial bending state in the specimen [1]. The setup of the carrier plate and the finite element contour of the resonant mode and normal stress during resonance are shown in Figure 1(a-c) [2]. More recently, our lab has been developing high-throughput methods in which multiple specimens are simultaneously tested in a revised carrier plate, as shown in Figure 1(d). In the time that it takes one specimen to fail, the remaining specimens accumulate the same number of fatigue cycles, thus reducing the remaining time to test the remaining specimens.



(a) (b) (c) (d)

Figure 1: *(a) Carrier-insert assembly mounted to shaker; (b) finite element contour of the resonant mode shape; (c) finite element contour of the normal stress during resonance [2]; and (d) finite element contour of the resonant mode shape in a planned multi-insert assembly [3].*

In the original single-insert technique, failure is determined by monitoring the resonant frequency of the carrier assembly. When the resonant frequency drops below a given threshold, the frequency drop corresponds to significant damage in the specimen. However, the inclusion of multiple inserts raises uncertainty as to how much damage has accumulated in each specimen at the point of the frequency drop. Thus, my research will aim to develop an alternative method to assess damage independently in each specimen by running a DC current through each electrically conducting specimen and monitoring for small changes in resistance. As fatigue damage accumulates, small micro-cracks will form in the gauge section of each specimen, thereby reducing the cross-sectional area through which current can flow, thus changing the resistance of the test specimen. By monitoring each specimen independently, I will be able to better identify which specimen has failed.

Objectives

- **Objective 1 (Summer 2021):** Perform **single-specimen** fatigue and voltage tests to quantify the relationship between resistance change and damage accumulation for a single specimen and define the voltage drop criterion.
- **Objective 2 (Fall 2021):** Perform **multiple-specimen** fatigue and voltage tests and use the previously determined voltage drop criterion to determine the damage in individual specimens.
- **Objective 3 (Spring 2022):** Repeat single-specimen fatigue and voltage tests **at high temperature** to determine if the voltage drop criterion holds in a high temperature setting.

Plan to Meet Objectives

Objective 1 (Summer 2021): I will assemble an electrically isolating, single-specimen carrier plate as shown in Figure 2 to allow for voltage measurements across the specimen. The designed carrier plate will be used to perform fatigue tests while measuring the specimen's voltage and the plate's resonant frequency. The voltage will be monitored in two ways: continuous measurements during live testing, and periodically pausing each test to confirm the resistance measurements manually. The voltage data will be used to quantify the relationship between the specimen's change in resistance and the damage accumulation indicated by the frequency drop criterion. This relationship will become the voltage-drop failure criterion for each specimen in a multiple-specimen test.

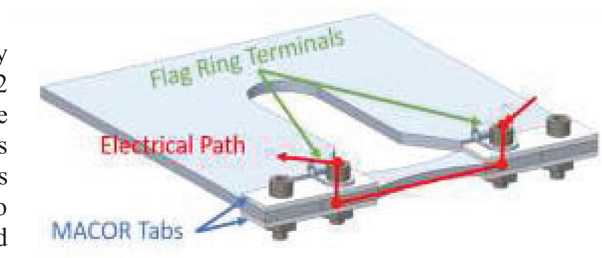


Figure 2: *Schematic of the revised single-insert assembly to electrically isolate insert specimens from the carrier plate.*

Objective 2 (Fall 2021): I will assemble an electrically isolating, three-specimen carrier plate similar to the single-specimen carrier plate. The three-specimen plate will be used to perform fatigue tests while measuring each specimen's voltage (independently) and the plate's resonant frequency. The voltage measurements will be analyzed to quantify the damage accumulation in each specimen.

Objective 3 (Spring 2022): I will repeat the single-specimen fatigue and voltage tests while heating the specimen with an induction heater to test the application of the voltage drop criterion in a high temperature setting. However, since induction heating is performed via magnetic fields, it is likely to interfere with the continuous measurements during live testing. Thus, the high temperature tests may rely more heavily on the manual voltage measurements.

Personal Relationship to Project

My goal after graduating is to pursue a career in research and aerospace engineering. This project is heavily related to aircraft design and maintenance, specifically the behavior of materials in aircraft engines. My involvement in this project will deepen my understanding of fatigue in thermoacoustic settings, which will make me a unique and valuable individual in my workplace. Therefore, this project will begin my work in the aerospace field. Additionally, this project will allow me to apply my understanding of multiple engineering concepts, including solid mechanics, vibrations, material science, and circuit theory. Having this comprehensive experience will guide me to becoming a successful engineer.

References

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[2] J. Bruns, A. Zearley, T. George, O. Scott-Emuakpor, and C. Holycross, "Vibration-Based Bending Fatigue of a Hybrid Insert-Plate System," Exp. Mech., vol. 55, no. 6, pp. 1067–1080, Mar. 2015.

[3] R. B. Berke, B.A. Furman, C.M. Holycross, O. Scott-Emuakpor, "Damage Accumulation in a Novel High-Throughput Technique to Characterize High Cycle Fatigue," Journal of Testing & Evaluation, vol. 49, published ahead of print 09 July 2020.