Design and Evaluation of a Test Device for Thermal-Acoustical-Mechanical Fatigue Experiments

Michael Sedlack[1], Abdi Jasmin[1], Philip Lavandera[1], and Ali P. Gordon[2]
University of Central Florida, Orlando, FL 32816, USA

Ravi Penmetsa[3]
Structural Sciences Center, United States Air Force Research Laboratory, Wright-Patterson, OH 45433, USA

In light of the combined extreme environment to which hypersonic fuselage components will be subjected, a unique test platform has been developed for evaluating materials and structures under service-like conditions. Typical ascent-cruise-descent missions will expose panels to thermal cycling, while aerodynamic pressure facilitated by Mach cruise speeds will superimpose mechanical vibration at acoustic frequencies. Additionally, the geometric constraint to be placed on these relatively thin structures will cause conventional mechanical fatigue with compressive mean stress. A Sanderson universal column buckling test frame has been configured to allow for closed-loop feedback control of cyclic mechanical, thermal, and acoustic loading. The graphical user interface (GUI) associated with this first-of-its-kind test device allow users to design cyclic load profiles that idealize the thermo-acousto-mechanical loading of critical panels. Calibration methods of individual and combined cyclic waveforms are shown. Sample waveforms are generated. Performance metrics and feature sets for a more sophisticated test bed are provided.

Nomenclature

δ_x	=	Horizontal deflection [mm]
δ_y	=	Vertical deflection [mm]
ε	=	Strain [mm/mm]
σ	=	Stress [MPa]
τ	=	Dwell period [s]
A	=	Cross-sectional area [mm^2]
f_a	=	Acoustic frequency [Hz or s^{-1}]
I	=	Moment of inertia [mm^4]
P	=	Compressive Load [kN]
ΔT	=	Temperature Range [°C]
T	=	Temperature [°C]
t	=	time [s]

I. Introduction

CLASSICAL prognostics methods are geared towards estimating fatigue response under situations where load profiles are sustained throughout the life of the component. For example, Coffin-Manson with a generic mean stress corrector is used for zero-to-compression loading under isothermal low cycle fatigue (LCF) conditions. Literature shows that when the mechanical load on totally or partially constrained structure is driven by time-dependent thermal stresses, fatigue life is reduced by an order of magnitude or greater. A similar life reduction is observed when LCF-tested materials are super-imposed with very high cycle fatigue (VHCF). In order to develop

[1] Undergraduate Reseaerch Asst., Dept. of Mechanical & Aerospace Engineering, 12760 Pegasus Drive, Non-Member.
[2] Associate Professor, Dept. of Mechanical & Aerospace Engineering, 12760 Pegasus Drive, Non-Member.
[3] Mechanical Engineer, Aerospace Systems Directorate/RQHF, 2790 D Street, Associate Fellow

the next generation of lifing methods for hypersonic vehicles, test platforms are needed to vet materials under combined extreme environments.

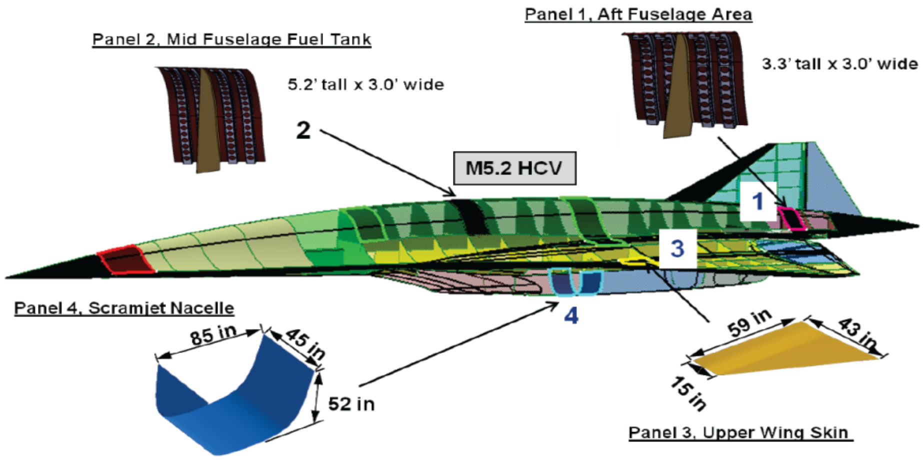

Figure 1. Critical panels of the DARPA Falcon HTV-3X designed for Mach 5.2.

The primary design drivers of planned vehciles are facilitated by fluctuating pressures resulting from turbulent separated flow and shock interaction. Transient, quasi-static thermal conditions will lead to evolving mechanical properties. Geometric constraint will facilitate thermal stresses. A candidate vehicle along with critical panels is shown in Fig. 1. In many instances buckling and crippling will be the design limiting failure mode. The consequent mechanical failure mechanism could consist of LCF, VHCF, creep, coupled environmental-fatigue, and combinations thereof.

Although some test devices have been developed to subject test articles to either TMF, thermo-acoustic, combined LCF and VHCF, and in some cases non-isothermal LCF with VHCF, a test bed for thermo-acoustico-mechanical fatigue where column buckling is allowed has yet to be developed.

II. Platform Design

A first of its kind test device has been designed to impart independently controlled temperature, mechanical, and acoustic loading to a slender test sample. To confer similitude between the thermoacoustic buckling conditions imparted to the component in service and test samples, a manual column test frame was mechanized. The test device is shown in Fig. 2 and briefly described in the following sections.

A. Hardware Design

A Sanderson universal column buckling test frame has been re-configured to allow for cyclic mechanical, thermal, and acoustic loading. Fixed-fixed, columnar specimen loading is generated by a servo-motorized lever arm. Eulerian buckling results from compressive loads exceeding the critical force of the specimen. Transverse vibration (150dB at 250Hz) is imparted to the gage section of the sample by means of an amplifier-driver-guide arrangement. Heat to the test sample is generated from a quartz lamp array.

To maintain a desired load, a variety of sensors is used to measure mechanical, thermal, and acoustic behavior displayed by the sample. A washer-type compression load cell is positioned at one fixed-end boundary of the column specimen. A displacement transducer is placed near at one-fourth of the height of the column (i.e., L/4) and oriented to record horizontal deflection, δ_H. While not explicitly recorded, the vertical deflection is determined from angular displacement of the motor and thread mechanics of the power screw. Several K-type thermocouples are spot welded to various locations along the primary stress axis of the test specimen. The mouth of the wave guide is placed a small distance from the middle of the test sample. Its transverse orientation imparts horizontal traveling waves to the sample. Multiaxis accelerometers are placed are along the legth of the test sample.

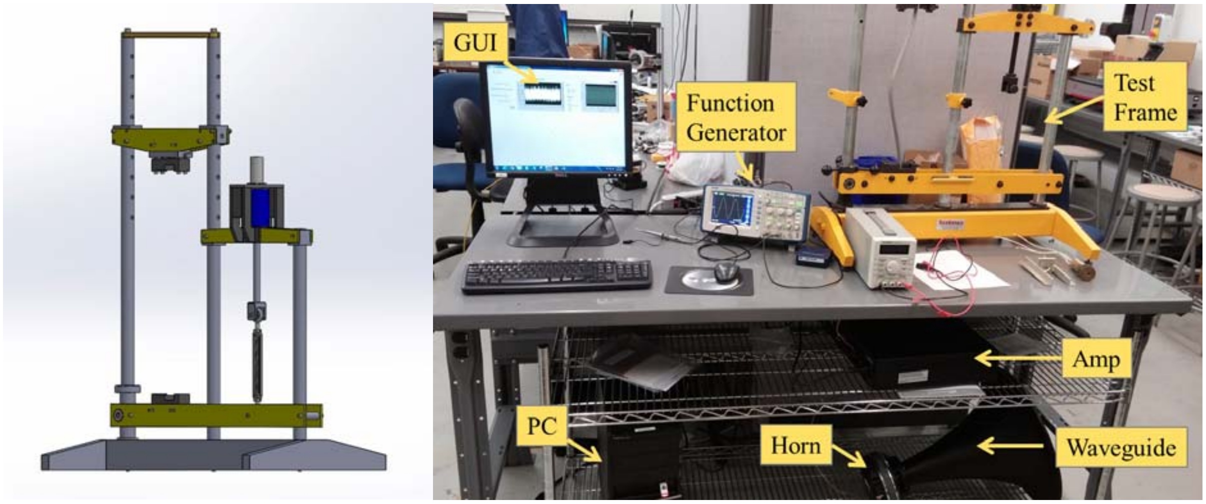

Figure 2. (left) Numerical concept of column buckling frame and (right) physical test platform.

B. Software Arrangement

Both sensors and load sources are connected through the user console via a National Instruments data acquisition chassis (NI cDAQ-9172 8-Slot). In several cases, signal amplifiers and/or fixed power supplies are needed to electrify the sensors and load sources. Various modules facilitate the conversion of signals from analog-to-digital and vice versa for inputs and outputs, respectively. The magnitude and frequencies of thermal, acoustic, and mechanical signals are maintained through closed-loop feedback control designed in a LabView virtual instrument (VI). For each case, a proportional-integral-derivative (PID) scheme is implemented.

C. Graphical User Interface

The LabView VI features an intuitive graphical user interface (GUI) that allows users with limited mechanical testing experience to design and conduct experiments. Raw test data is recorded to a single ASCII-formatted text file. All relevant test variables can be manipulated through the user menu and are as follows: (a) maximum and minimum temperature, (b) cycle period, (c) dwell period, (d) sound pressure level, (e) acoustic frequency, (f) acoustic waveform, (g) mechanical control mode, (h) mechanical load range, (i) mechanical load ratio, (j) thermal/mechanical phasing, and (k) data storage rate. Filename and directory are also specified via the GUI. An experiment can be paused or stopped using a bottom placed on the GUI.

D. Specimen Design

Several samples of multipurpose 304 stainless steel, having identically uniform cross sections (i.e., h = 3.18mm by b = 25.4mm) but a range of lengths (i.e., between L = 0.3m and 0.9m), were utilized in the test bed development. The specimens are tested in the unpolished condition, and they were incised from hot rolled plate stock (per ASTM A276). At room temperature, elastic modulus, *E*, is 193GPa, yield strength corresponds, *0.2%YS*, to 207MPa, and the coefficient of thermal expansion, α, is 5.3×10^{-6}°C.

III. Calibration

Prior to the performance of experiments, the various components included with the system were tuned. The sensors and load sources are associated with three subsystems: mechanical, acoustical, and thermal. Two types of calibrations were conducted: independent tuning and cross-tuning. In the former case, electrical components from either subsystem are tuned while the the other systems are at rest. For example, the piezo-based accelerometers where calibrated at room temperature. In the latter case, sensor outputs were correlated while multiple subsystems were active. The following sections describe the tuning modes for each subsystem in the test platform.

A. Electromechanical Subsystem

The compressive load cell (Futek model: LTD 400) was subjected to a known loads between 0kN (0V) and 3.7kN (2.1V). Known displacements between 0 (0V) and 15mm (10V) were prescribed to the spring-loaded, displacement transducer (Omega model: LD621-15). A high-torque servo-motor was used to drive a power-screw connected to the lever arm. Additional power is supplied to both the load cell, displacement transducer, and the motor via fixed DC power supplies. Input voltage was applied to the motor, and the resulting angular velocity (in rad/s) was determined through a stroboscope. For the motor, an H-bridge circuit combines the fixed power with oscillating signal from the chassis. Linear relationships for each of these devices were embedded into the LabView VI. The calibration curves for specimens of various lengths are shown at room temperature and at elevated temperature.

B. Electrodynamic Subsystem

An oscillatory voltage waveform (sinusoidal or triangular) of frequency, f_a, of 250 or 500Hz and amplitude of 328mV, is output from the NI cDAQ chassis to a 2-channel, dual-source power amplifier (Russound model: R290DS). A 8 or 16Ohm signal is sent to a 2” mid-range, compression driver (BMS model: 4591). A flat front, exponentially curved waveguide is flush-mounted to the driver. Pre-calibrated (10mV/g), miniature accelerometers (Piezotronics model: PCB 352B10) were attached to the tip of the waveguide and along the length of the sample. The calibration curves for specimens of various lengths are shown at room temperature and at elevated temperature.

C. Electrothermal Subsystem

Power from the arry of quartz lamps (Ushio model: 1000524-FFW JP120V) came from a fixed power supply modulated by the LabView VI output via a custom H-bridge circuit. The temperature was recorded at several lengths on a calibration test sample. A relationship was established between the temperature at the mid-point and end-point of the sample. Temperature at the end point was used for temperature control under constant and variable temperature conditions. Additional consideration was required to ensure that the temperature response of the sample during heating and cooling were identical.

IV. Test Profile

The flight plan of candidate reusable launch vehicles consists of take-off, cruise, and landing. While the take-off and landing portions of the history will each endure for approximately fifteen minutes each, the hypersonic cruise portion will endure for a ceiling of nearly one hour. Stress in some portions of the flight history will be dominated by mechanical loading, while others will consist of primarily acoustic vibration induced by aerodynamic pressure. Ostensibly, in-flight maneuvers will also impart low-rate/high-amplitude mechanical deformation. For the purpose of evaluating the performance of the system, two types of combined waveforms are evaluated: idealized and service-like. Each is described sequentially in the next sections.

A. Idealized

Experimental mechanics that focus on sample-sized fatigue test coupons are generally designed to characterize material behavior rather than component response. The main thrust is generate test data that will faciliate the development of mechanical properties utlized in modeling, simulations, and other methods. While some test coupons will be subjected to thousands of cycles, similar to a component, the temporal scales of cycle frequency can be orders of magnitude less than the actual component. Figure 3 demonstrates the first few cycles of the “idealized” combined load histories. Five temperature histories are available (T1 through T5). In the two cases were temperature is cycling, the cycle period is 360s. No dwell period is included. The acoustic load is either set to on or off for the duration of the test. A frequency, f_a, of 250 or 500Hz is applied. Several mechanical constraints are employed: (M1) unconstrained (load is held at zero to allow thermal cycling), (M2) fully constrained (the vertical displacement at the ends is fixed), (M3) partially constrained [average of (M1) and (M2)], and (M4) overconstrained [horizontal displacement generated by (M2) is doubled]. Selections (M1) and (M3) are conducted in load control while (M2) and (M4) are carried out under displacement control. While the thermal and mechanical profiles are triangular, the acoustic loading is sinusoidal. Data is recorded at 20Hz for the following cycles: 1 through 10, 11, 20, 21, 30, 31, and so on up to 100, 101, 200, 201, and so on.

B. Service-Oriented

While a 100-cycle idealized test described in the prior section would conclude at approximately 10 hours, the service-oriented experiments can endure for greater than an order of magnitude longer (e.g. 150 hours). Here 1hr dwell periods are included at the location of maximum compressive load. The temperature is held constant in the region. The acoustic load is active only during this dwell period (cruise) and not during the push (ascent) or pull (descent) portion. Other than these changes, the thermal profiles, namely T1 through T5, and mechanical controls, i.e., M1 through M4, presented in the prior section carrier over. During the dwell periods of test profiles with elevated temperature, creep deformation occurs. Specimens under load-control holds will exhibit creep, while samples under displacement control will show stress relaxation. A data recording rate of 4Hz in universally applied.

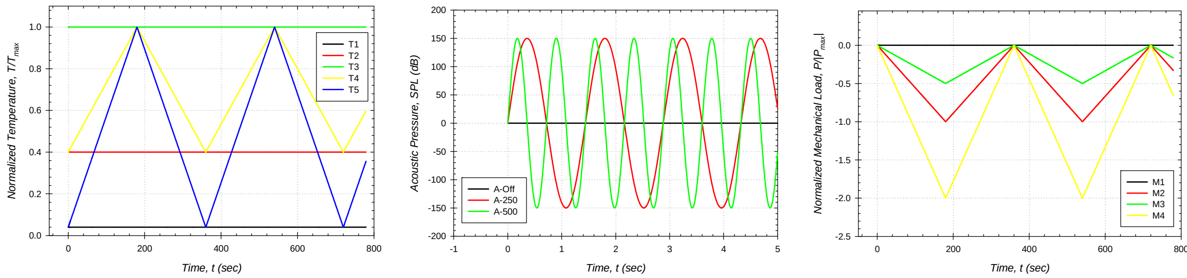

Figure 3. (left) Temperature, (middle) acoustic, and (right) mechanical waveforms generated by the test device.

V. Results

Performance attibutes of the of the test platform were studied for each of the individual subsystems and the system. For the mechanical loading subsystem, several combinations of compression amplitude and frequency were tested. Both displacement-based and load-based control modes were studied. Combinations of high amplitude and high frequency where the actual waveform departed from the desired signal are noted. The phase difference between actual and desired specimen temperature was determined for several temperature profiles. Sources of error for acoustic measurements in the presence of mechanical and/or thermal cycling are noted.

VI. Conclusion

A device was designed, fabricated, and evaluated for subjecting sample-sized components to super-imposed profiles of thermal, acoustical, and mechanical loading. The collective load profile endeavors to simulate the service condition to which critical hypersonic fuselage panels will be exposed. Calibration techniques for each loading mode, performance attributes and limitations, and avenues for further investigation are all described.

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