Real-Time Micro-Explosive Damage Detection in an Unmanned Rotorcraft Vehicle Using Embedded Sensing

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ABSTRACT

Demonstration of damage detection and related Health and Usage Monitoring System (HUMS) technologies for condition-based maintenance (CBM) is most convincingly done through flight testing. Demonstration of damage detection using manned aircraft may not be feasible due to airworthiness requirements which must ensure safety of the flight crew. However, demonstrations using an Unmanned Air Vehicle (UAV) provide unique opportunities to test the in-flight detection and monitoring of damage to critical aircraft components without risking a flight crew. UAV demonstrations can therefore initiate faults into primary aircraft structure while in flight to study real-time fault-sensing capability of advanced sensors. The U.S. Army Research Laboratory (ARL) is collaborating with Acellent Technologies to demonstrate the diagnostics capability of advanced sensor systems to detect embedded flaws/damage on structural components using an unmanned rotorcraft vehicle (URV). ARL developed innovative techniques to initiate controlled flaw/damage using micro-explosives on a principal structural element (PSE) on the URV. The selected PSE on the URV is a side plate, shielding the engine compartment of RAPTOR 90. Two Acellent SMART Layer sensor patches were surface bonded to the damaged panel. The installed sensor systems can actuate and receive guided Lamb waves at multiple frequencies simultaneously. Data collected from the damaged PSE, compared with the baseline signals collected prior to the damage, showed change in amplitude and phase of the signals, indicating the presence of damage. Analysis of the signals by the Acellent Smart Patch software indicated a structural change within the PSE from the damage initiated by the micro-explosive. A ground-based flight test stand was developed and built to inexpensively address concerns about the safety of personnel in the area of operation of the selected URV. Preliminary tethered flight tests were then conducted as a risk reduction to planned free flight tests within the Army airspace. An autopilot was developed and control parameters were determined. The tethered flight tests showed that stable, autonomous flight could be achieved.

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INTRODUCTION

Development of structural health monitoring (SHM) is complex and involved numerous technologies, but it shows tremendous potential for safety and economic benefits. Demonstration of structural damage detection capability and other related technologies potentially used for CBM via flight testing using manned aircraft may not be feasible due to airworthiness requirements and safety of the flight crew[1]. This paper details the collaborative research among the Mechanics and Autonomous Systems Divisions of the ARL Vehicle Technology Directorate (VTD) and Acellent Technologies to advance crack and damage detection capability and other related technologies to be incorporated into HUMS. The research demonstrated crack and damage detection capability on a selected URV. The research main steps are:

- Select a URV with a typical PSE.
- Select suitable metallic and composite materials to be used in the duplication of the selected PSE. Fabricated two PSEs in accordance with the manufacturer's design.
- Obtain selected materials properties and fatigue crack growth (FCG) characteristics to fully understand the materials behavior under loading.
- Design and fabricate a small electro-explosive device (EED) to rapidly introduce a predictable structural flaw in the fabricated PSEs.
- Select a crack/damage detection system to be installed on the selected URV to monitor the fabricated PSEs.
- Develop a strategy for safely and inexpensively accumulate flight time, in lieu of conducting flight tests at an Army airfield, using the selected URV equipped with crack/damage initiation system and a low-cost HUMS to collect data. Develop risk mitigation and demonstrate full understanding of progressive failure of fabricated PSEs and controlled risks to secure the Army safety office approval for actual flight testing.
- Conduct flight tests of the selected URV with fabricated PSEs and installed damage detection sensors.
- Analyze the data to establish flaw detection and qualitative flaw location. Establish the probability of detection of the selected monitoring system.

EXPERIMENTAL TEST SET-UP & PROCEDURE

In collaboration with the ARL-VTD Mobility and Manipulation Team at the Aberdeen Proving Ground (APG), four URVs have been made available. The available URVs include the Yamaha RMAX, Vario XLV, Raptor 90, and T-Rex 450. The URVs are shown in Figure 1 and their development is described in [2]. One of the smaller URVs, the Raptor 90, is currently used to gain full confidence prior to incorporating flaws into selected PSEs using a larger URV. The Raptor 90 URV side plate structure was selected as the PSE to assess and demonstrate advanced sensor system capabilities for damage detection and damage growth monitoring. The exploded view of the Raptor 90 airframe is illustrated in Figure 2 a), in which the side plate is indicated.

A controlled crack/flaw initiation technique, which could potentially be remotely activated in-flight, was developed with support from the ARL Sensors and Electron Devices Directorate (SEDD) Intelligence, Surveillance, and Reconnaissance (ISR) Technology Integration Branch. This technique uses micro-explosives to create flaws at a desired location on a selected component. An M100 electric detonator was chosen for the initial flaw initiation experiments. The M100 occurs in many Army munitions and contains approximately 32 mg of explosive [3]. It is small (0.100 inches (2.54 mm) in diameter and 0.25 inches (6.35 mm) long), which makes it easy to fit the detonator at almost any point on the airframe. Though small, the M100 is a sensitive explosive detonator requiring care in handling and protection from static discharge. Other methods were considered, including percussion primers and piston actuators. A percussion primer is typically found in the base of a cartridge, *e.g.*, in small arms ammunition.

Figure 1: ARL Available URVs

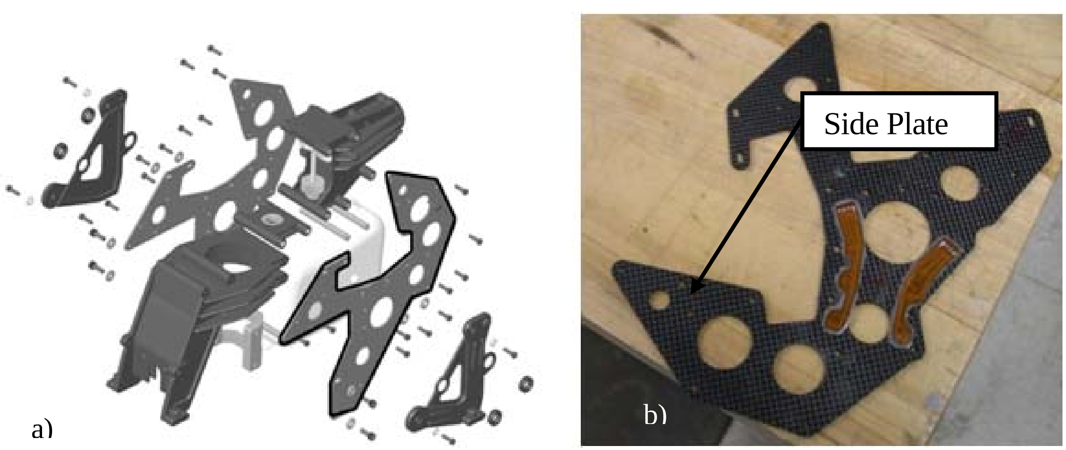

Figure 2: a) The Raptor 90 Airframe and Selected PSE b) The Side Plate with Sensors Installed

The primer functions a pyrotechnic mixture when impacted by a weapon's firing pin. While safer to handle, its output would be too weak to cause damage. In addition, for in-flight operation, a large, heavy solenoid and firing pin would be required which would severely restrict placement of the device on the airframe.

Piston actuators resemble detonators but instead of explosive they contain a pyrotechnic mixture and a metal piston. When functioned electrically, the mixture rapidly generates gas which moves the piston forcefully from the end of the device. The piston is retained at the end of its stroke. The actuator offers ease of initiation and containment; no fragments are generated. The disadvantage is the amount of force produced, typically a few tens of pounds at most. This can still equate to a fair amount of pressure as it is applied over an area of 0.125 inches (3.175 mm) in diameter. Unfortunately, no piston actuators were readily available at the time of the test.

The M100 was chosen as it was virtually certain to cause some degree of damage. If the damage were too great it could be reduced by introducing an attenuating material. Its small size, low energy requirements, and ready availability made it the choice of the firing material for the first round of testing. To decrease the level of damage imparted by the M100, an attenuating material was placed between the M100 and the plate to be damaged. The attenuating material, commonly known as butterboard, is a packaging material for explosives. Initial flaw initiation tests were performed on square plates made of aluminum 5056. These tests were followed by controlled flaw initiations on two versions of the Raptor 90 side plate, one made of carbon fiber composite and one made of aluminum alloy 5056. All flaws were created in the laboratory on isolated side plates.

Acellent SMART Layer sensors [4-7] were selected and installed on a composite Raptor 90 side plate, after flaw creation, as shown in Figure 2 b). Each of the Kapton-based sensor strips contained three piezoelectric transducers capable of generating Lamb waves. Each transducer can detect the Lamb waves produced by the other transducers. The flawed, instrumented side plates were then connected to Acellent ground-based instrumentation, which interrogated the sensors and collected the resulting data. The data was examined with the Acellent SmartPatch software using time-history analysis to generate the damage image, Figure 5 b). To increase flexibility in sensor installation, which in turn facilitates optimization of sensor location, a version of the side plate was fabricated without lightening holes. The lightening holes are the seven largest holes which appear in Figure 2 b). Later iterations of this experimental effort will focus on this design.

An initial flight test with the sensor installed on the PSE was completed. Sensor integrity was confirmed via comparison of post-flight data to baseline data collected pre-flight.

Current operational procedures for UAVs prohibit flying an unsafe aircraft. Using a ground test stand allows operation of URVs having airframes with structural flaws and enables testing of real-time structural health monitoring sensors and flaw detection systems. The stand was enclosed in a safety cage to minimize potential risk. A portion of the cage is visible as shown behind the RMAX in Figure 1. The stand and cage aim to allow the selected URV to achieve autonomous captive flight to accumulate flight hours without the need to conduct free flight testing, reducing risk and cost for experiments with HUMS on defect-embedded rotorcraft components.

The ground test stand resembled a design of the University of Texas at Austin [5] but incorporated increased overall strength and substituted a spring for the gas-filled

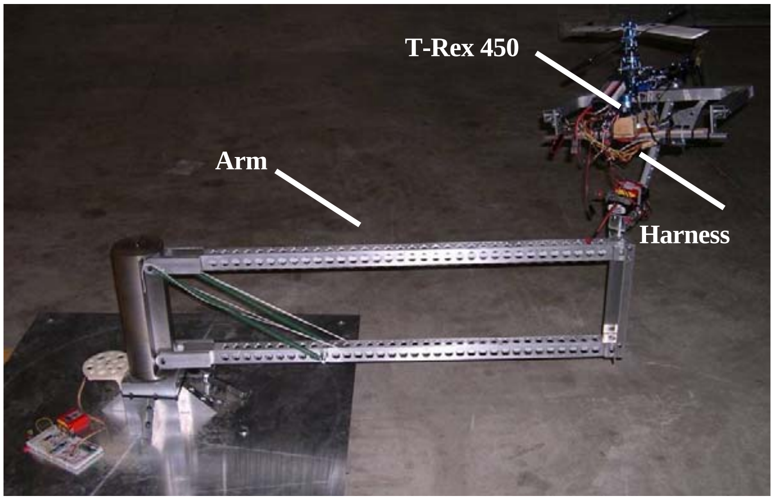

Figure 3: Ground-based Flight Test Stand with T-Rex 450

Table I. Degrees of Freedom for Ground Test Stand

Pitch	Roll	Yaw	Translation & Elevation
±30°	± 10° *	0 to 360°	Limited by 1 m Arm (4-bar Linkage)
* Roll artificially limited to increase margin of safety			

strut, which compensated for arm weight. The stand's harness can accommodate URVs having rotor diameters of 0.6 to 1.5 m. The URV movements allowed by the test stand appear in Table I. Initial flights to assess the test stand were carried out with a small URV, the T-Rex 450, which was mounted on the test stand as shown in Figure 3. Manual flights were performed first. Then system identification experiments were performed to develop controls for stabilizing the URV autonomously on the ground test stand [6]. Also, a previously developed microcontroller-based autopilot [7,8] (ARL Open Autopilot) was modified for experiments on the stand with the T-Rex 450 URV. This autopilot allows custom control software to be written and developed quickly. It is also small enough and light enough to be flown on the T-Rex 450.

RESULTS AND DISCUSSION

Table II summarizes the test parameters and damage achieved in each flaw initiator test. A typical hole and typical dimples appear in Figure 4a) and b). The flaw created on the carbon fiber composite side plate using the micro-explosive device appears in Figure 4 c), in which a crack along with possible underlying delamination, not readily visible, connects the two holes. Results were most sensitive to the presence/absence of the butterboard attenuator. In aluminum, the butterboard moderated damage from a through-hole to a dimple while, in composite, the crack width was decreased from 7/16 inches to 1/8 inches wide (11 to 3 mm). Because the detection of a crack in metallic components is an important SHM problem, neither the through-holes nor the dimples induced on the aluminum are entirely satisfactory.

Table II: Flaw Initiation Tests

Test No.	Test Plate	M100 Orientation to Plate	Butterboard Thickness, inches (mm)	Mount Location Reference	Distance from Reference, inches (mm)	Damage & Size, Inches (mm)
1	Solid 5056 Al	Normal	None	Edge	0.25 (6.35)	Jagged Hole, 1/16 (1.6) dia. Edge bend Dimple, 1 (25.4) dia.
2	Solid 5056 Al	Normal	None	Edge	1 (25.4)	Jagged Hole, 1/16 (1.6) dia. Dimple, 5/8 (16) dia.
3	Solid 5056 Al	Parallel	None	Edge	1 (25.4)	Rough Pitting, Scratches Dimple, 5/8 (16) dia.
4	Solid 5056 Al	Normal	0.037 (1)	Edge	2 (50.8)	Dimple, 5/8 (16) dia.
5	Solid 5056 Al	Normal	0.100 (2.54)	Center	1 (25.4)	Dimple, 5/8 (16) dia.
6	Raptor 90 Side plate 5056 Al	Normal	0.037 (1)	Between Lightening Holes	Midway	Dimple, 5/8 (16) dia.
7	Raptor 90 Side plate Composite	Normal	0.037 (1)	Between Lightening Holes	Midway	Slight crack, mountside Large crack, underside, 7/8 (22) long, 1/8 (3) wide Delamination
8	Raptor 90 Side plate Composite	Normal	None	Between Mounting Holes	Midway	Slight crack, mountside Large crack, underside, 7/8 (22) long, 7/16 (11) wide Small through hole Delamination

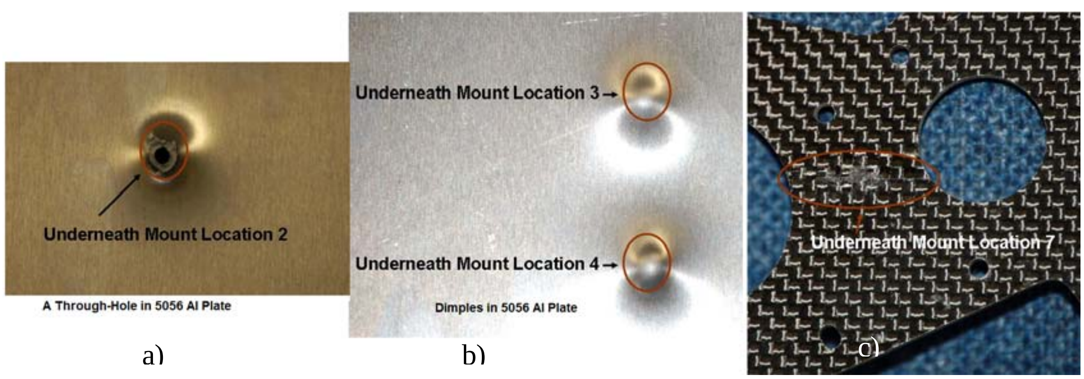

Figure 4: a) & b) Underneath M100 Test on Flat Al 5056 Plates c) on Composite Raptor 90 Side Plate

The Lamb waves generated by transducer 3 and the sensor signal received by transducer 4 is shown in Figure 5 a). The sensor locations and numbers are illustrated in Figure 5 b). Transducers 1, 2 and 3 were used as actuators and transducers 4, 5, and 6 were used as sensors, resulting in a total of 9 actuator-sensor paths that formed a grid encompassing the target damage detection monitoring area. The baseline data, collected before initiation of damage, appear in blue while the post-damage data appear in red. Acellent ACESS software post-processed data from the 9 actuator-sensor paths, which have been used to generate the diagnostic image, appears in Figure 5 b). Contour colors graduate from blue to red to indicate the probable damage location. The Acellent's data collection hardware uses discrete actuator and sensor connectors, facilitating low noise/low crosstalk signal generation and capture. Close sensor spacing can be utilized without signal degradation, allowing for high-resolution damage detection.

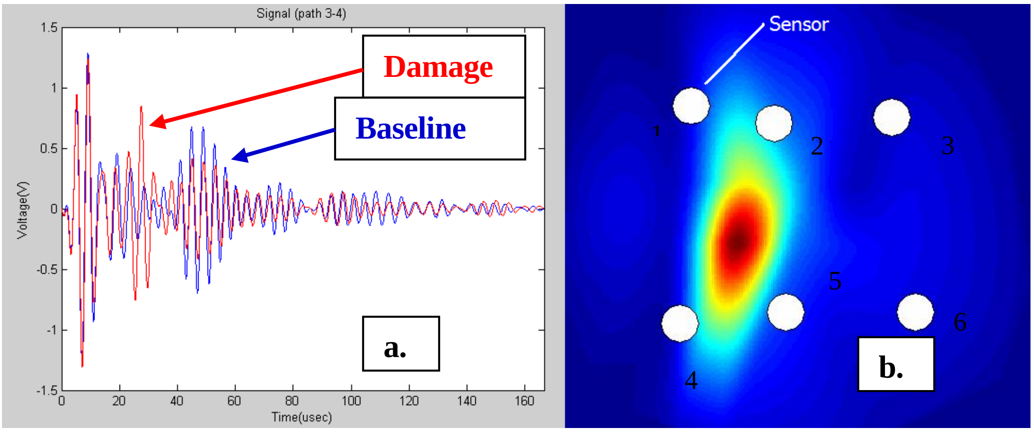

Figure 5: a.) Baseline and Post-Damage Data b.) Post-processed Image

As a testament to the benefit of ground test stands and flight safety, during an experiment with a T-Rex 450 URV, the tail rotor belt broke. In free flight, the URV and autopilot may have been irreparably damaged. On the test stand, the URV spun briefly and harmlessly in the harness. Only the belt needed to be replaced in order to continue the experiments.

The harness allows the URV to pitch, yaw, and, roll, but its attachment points define axes of rotation, which do not pass through the center of gravity of the URV. Hence, the harness does not permit the same rotation of the URV, which would occur in free flight. To allow natural rotation, a custom harness needs to be fabricated for each URV, and the URV airframe will possibly need to be modified to accommodate the proper attachment points to mitigate the effect of the constraints. Issues will still remain with different vibration frequencies being generated in captive flight versus free flight. Additionally, it requires precise navigation to follow the constrained path of the test stand to minimize forces generated by the test stand and acting on the URV.

Early results from the ground test stand indicated that aircraft stability in autonomous flight was achieved. Control system identification of an operating rotorcraft on the ground test stand was successfully performed using the ARL Open Autopilot. As currently configured, the gains for control of pitch and roll of the helicopter computed for captive flight cannot be directly applied to free flight.

CONCLUSIONS

The RAPTOR 90 URV and its side plate structure were selected to assess and demonstrate Acellent system capabilities for damage detection and damage growth monitoring. Controlled flaw initiations were accomplished with an electro micro-explosive technique. The flaw initiator has the potential to be remotely triggered to create cracks/flaws on structural components during flight. Its output can be attenuated to deliver varying degrees of damage to the component. Its small size and light weight allow it to be easily mounted on a surface. The URV structural element fabricated from ductile 5056 aluminum alloy did not lend itself to cracking by micro-explosive. The carbon fiber component developed macroscopic cracks and delamination even though the surface, where the M100 was mounted, displayed little visual indication of extensive damage. The selected sensors survived initial flight tests, and the damage detection system demonstrated flaw detection and qualitative flaw location on a quiescent structural component in a laboratory setting. If some disparities between the ground test stand flights and free flight are acceptable, then the relatively inexpensive prototype ground test stand and autopilot developed for this program can safely accumulate flight hours, at low cost, for validating HUMS detection of damage in rotorcraft PSEs.

FUTURE DIRECTIONS

- A crack is the desired flaw for the aluminum component. More research will be conducted on initiation of flaws in a structural element fabricated from the less ductile 7075-T6 aluminum alloy.
- Improvements to the ground-based flight test stand will be made to reduce the effects of the harness constraints and to allow better determination of free flight control gains.
- A larger URV will be instrumented with a selected mini-HUMS and sensors.
- Acquire full understanding of the FCG of fabricated PSEs, potential risk, and safety issues during flight
- Flaw initiation will occur during tethered flight of an instrumented URV and, potentially, during free flights after safety concerns have been successfully addressed.
- Further evaluation of the system will include evaluation of receiver operating characteristic (ROC) curves [9,10] to characterize damage detection probability versus false alarm rate.

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