

COMBINING SENSORS WITH AIRBORNE TELEMETRY INSTRUMENTATION TO MAKE RANGE MEASUREMENTS AND OBTAIN AERODYNAMICS

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ABSTRACT

Obtaining a projectile's free-flight motion profile and its aerodynamic coefficients is typically accomplished at indoor test ranges using photographic techniques synchronized to timing stations. Since these ranges are relatively short, many discrete tests are necessary to compile a complete understanding of the projectile's behavior. When Time Space Position Information (TSPI) is requested over long-range flights, it has been gathered with expensive video, laser, and radar trackers. These can be inaccurate at times and are limited to locations where the range equipment is able to track the projectile's entire flight. With the ever-increasing sophistication of ordnance, such as smart and competent munitions that have multi-stage thrusting and maneuvering capability, it is becoming increasingly difficult to make the necessary measurements using current measurement techniques.

Microelectromechanical Systems (MEMS) sensors and other electro-optical and magnetic sensors referenced to the sun and earth allow the projectile's angular rates (spin, pitch, and yaw) and accelerations (axial and radial) to be measured throughout the flight. These sensors have been packaged into miniaturized telemetry instrumentation systems and placed within empty voids of the munition or in place of the fuze or warhead section. By combining this sensor data with a 6-DOF trajectory code, many of the projectile's aerodynamic coefficients including drag, static moment, and damping moment over a large Mach Number range and over multiple flight paths have been obtained. These techniques decrease the number of test shots required, reduce the complexity of the test setup, and reduce the test costs. Test data from instrumented tank, artillery, and rocket flight tests are presented in this report to show the current capability of making in-flight measurements using telemetry-based techniques.

KEYWORDS

sensor, microelectromechanical systems (MEMS), flight test, high-g, inertial measurement unit, aerodynamics

INTRODUCTION

The Advanced Munitions Concepts Branch (AMCB), U.S. Army Research Laboratory (ARL), has been providing in-flight measurements of direct- and indirect projectiles, rockets, and missiles using customized FM/FM analog telemetry systems to transmit the data for nearly 20 years. AMCB has worked with many U.S. Department of Defense (DOD) agencies, U.S. military contractors, and military services from NATO friendly countries to mix and match various sensors, transmitters, antennas, and power supplies for the desired measurement application depending on the space available, g-loading, and other environmental conditions. Recently, the Hardened Subminiature Telemetry and Sensor System (HSTSS) Program that is jointly sponsored by the DOD and the U.S. Army, has been developing and demonstrating a new generation of high-g technologies to support these airborne, gun-launched test measurements (Faulstich et al. 1996, D'Amico 1998). Major thrusts are being made to increase the capabilities in the following areas: transmitters, power supplies, electronic packaging, and sensors. The following report briefly summarizes the measurements that can be made today, describes the ground and flight test capabilities, and describes the future trends in range measurement techniques.

MICROMACHINED SENSOR TECHNOLOGY

Today, there are about ten manufacturers making MEMS accelerometers, primarily for the automotive air bag market. Analog Devices (AD) was one of the firsts to manufacture such a low-cost surface-micromachined direct-current (DC) accelerometer. The device comes complete with all conditioning circuitry built onto the same chip. Their accelerometer line and measurement ranges have been expanding from the ADXL05 and ADXL50 in a 10-pin T0-100 metal can, to the newer ADXL105, ADXL150, ADXL181, and ADXL190 in a 14-pin ceramic package. They currently range from 5 to 500 g's. Performance specifications for making in-flight measurements are close to those required for T&E applications. Prices for these accelerometers are about \$20. AMCB obtained a small quantity of accelerometers to demonstrate high-g launch survivability and subsequent operation in low-g flight environments typical of artillery projectiles. MEMS accelerometers from Motorola and Endevco have also been ground and flight-tested with much success. Still others have been surveyed for their performance specifications, but not yet tested. There is interest in making in-bore acceleration measurements but there isn't a commercially available MEMS device that measures up to 100,000 g's.

MEMS rate sensor development is trailing that of the accelerometers predominantly because they are electronically more complex. There are a few companies with products that are available. Research and development, fueled by the auto industry, is directed at active handling and platform stabilization systems. Auto specifications for the gyro's bias stability is 1 °/sec. When temperature compensated, these devices are approaching those

needed for rocket/missile IMUs but are still an order of magnitude away from projectiles with long flight times that require higher performance.

Another commercial market for rate sensor that has grown considerably in the last few years is the camcorder industry. Image stabilization is becoming almost a standard feature for most analog and digital video cameras. The most common method of measurement of either tuning fork or other vibratory device uses the Coriolis force. An example is Murata's triangular prism, which has been shown to survive over 100 g's and capable of measurements past 300 deg/s. Such devices have been shown to be suitable for limited test and evaluation purposes in military applications.

Defense Advanced Research Projects Agency (DARPA) MEMS is supporting the production of such a micromachined silicon inertial rate sensor. A MEMS gyroscope was developed through an alliance between Boeing North American (now Honeywell) and Draper Laboratory, as reported by Connelly and Brand 1997. The project's intent was to transition the MEMS technology from a research and development environment into a COTS product. AMCB was a DOD advisory member to identify potential military applications. The Technology Reinvestment Program will identify the necessary modifications to the packaging and performance through testing of the automotive quality gyros. Prototypes have undergone extensive qualification testing at Boeing. AMCB was given a sample to test in May 1997. The intent was to verify Boeing's preliminary performance specifications and perform additional specialized tests designed to check the gyroscope's capabilities as an IMU for strapdown projectile applications.

On rolling projectiles, the influence of spin on accelerometers and gyroscopes is dramatic as will be evidenced in other sections of this paper. A measure of the projectile's spin rate will be required to compensate for these spin-induced errors. Magnetometers are being utilized to determine the spin rate and roll position. The SCSA50 is a miniature, low-cost, magnetic angular rate sensor that is capable of providing one count per revolution of a projectile spinning in space. Under an engineering services contract, sensors were supplied to AMCB for gyroscopic, high-g shock, performance, and flight testing with good results reported by Davis et al. 1997. Sensor Applications designed the sensor using giant magnetoresistance ratio (GMR) materials. The sensor is capable of providing both a digital and an analog output, referenced to half of the supply voltage. The expected cost of the sensor will be around \$50 in low volume. Magnetic spin sensors, with resolution in the nanoTeslas, are also under development. DARPA is currently funding a MEMS magnetometer effort. This work is headed by Johns Hopkins Applied Physics Laboratory (Wickenden et al. 1997).

HIGH-G SHOCK TESTING

The harsh launch and flight environments of gun-launched projectiles, including high accelerations, pressures, temperatures, and vibrations, make it difficult for on-board sensors and electronics to survive and function properly. Therefore, components are routinely subjected to a laboratory simulation of launch accelerations on a shock table and then graduate to an air gun to assess survivability limitations. Over the past few years, a number of MEMS accelerometers have been shock tested. Due to their small size and low mass, results have shown durability better than expected.

Unpowered ADXL05 and ADXL50 accelerometers were tested on AMCB's IMPAC66 HVA shock table during tests performed by Davis. This machine uses high-pressure gas to raise and lower a drop table. An elastic cord assists in pulling the drop table toward the anvil. The machine has the capability of producing up to a 35,000-g environment. The acceleration is controlled by the height that the table is released from and the thickness and type of damping material placed between the anvil and the drop table. Accelerometers were oriented in both the axial and transverse orientations within an aluminum fixture and subjected to shocks up to 35 kg's with <1-ms duration. The shock amplitude was increased with each test until failure occurred. Minimum shock with a failure occurred near 20 kg's. Even with limited sample size, it was clearly evident that these accelerometers were consistently able to survive extreme artillery-level gun launch accelerations.

Follow-on air gun tests showed further resilience to shock. The test consists of independent launches of an aluminum carrier body by a 4-in high-pressure air gun. After exiting the tube, the carrier body impacts a mitigator and momentum exchange mass to cause the deceleration of the carrier. Various mitigator designs are available to tailor the impact-pulse amplitude, rise time, and duration. A limited number of units were shocked up to 95 kg's with 1-ms duration. Failure occurred at a minimum shock of 50 kg's. When failure did occur, the cause was by stiction or a detached beam.

More recently, ADXL150 and ADXL181 accelerometers have been shock-table and airgun tested with more elaborate test setups. Accelerometers were powered and their output was recorded. Figure 1 shows the raw data for a typical accelerometer before, during, and after shock-table testing. The initial 0-g bias level was 2.5 V. The accelerometer was clipped during the shock but then recovered. It rang during vibrational movement of the table until it settled. Scale factor errors and 0-g bias shifts were measured and found to be minimal. This agreed with air-gun tests of unpowered ADXL150s and ADXL181s performed by Brown and Davis (1998).

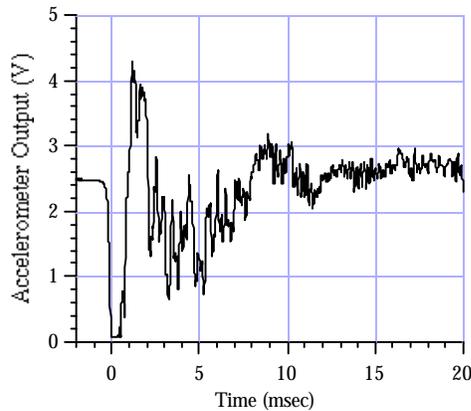


Figure 1. Accelerometer output from shock-table test.

FLIGHT INSTRUMENTATION PACKAGES

Tank, artillery, missile, and rocket bodies have been instrumented with customized telemetry packages without major modifications. The instrumentation is placed within voids of the projectile or in place of the fuze or warhead section. Many different munition types have been instrumented to obtain flight data. Figures 2 through 4 show three examples of munitions tested along with their instrumented telemetry sections. Brown et al. (1996) flight-tested rockets with yawsondes, accelerometers, and strain gages, shown in Figure 2. Davis et al. (1997) flight-tested artillery projectiles with accelerometers in axial and radial orientations, shown in Figure 3. Figure 4 represents recent HSTSS miniature packaging and sensor accomplishments through the flight testing in a tank munition. These three examples utilized a variety of transmitter and power supply options.



Figure 2a. 2.75-inch rocket.

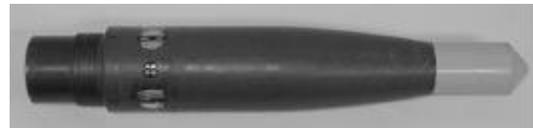


Figure 2b. Instrumented rocket warhead section.



Figure 3a. Artillery projectile.



Figure 3b. Instrumented NATO standard fuze.



Figure 4a. 120 mm tank kinetic energy projectile.



Figure 4b. Instrumented tracer-well section.

In designing an instrumentation package the outside configuration and physical characteristics (i.e., mass, moments of inertia, and center of gravity) of a particular munition are maintained. Both computer-aided design (CAD) and finite-element analysis (FEA) are tools used in assuring similitude.

Prior to testing, the physical measurements including weight, center of gravity (cg) from base, axial moment of inertia, and transverse moment of inertia are measured. Sensor calibrations that yield the individual sensor scale factor, bias, and exact location (position and orientation within the flight package) are also performed. This information can be used to generate the theoretical sensor output when combined with a 6-DOF trajectory simulation program and a sensor model. Using this simulated output and the resulting field data, comparisons to the in-flight sensor measurements can be made.

Test range instrumentation at the gun site may include tracking radar, muzzle velocimeters, breech/chamber transducers, and copper crusher gages. A telemetry instrumentation van, manned by AMCB and other required personnel, is used to acquire the telemetry data.

IN-FLIGHT SENSOR MEASUREMENTS

Conventional ARL yawsondes employ two optical sensors to determine the motion of the projectile with respect to the sun. A diagram is shown in Figure 5. A typical yawsonde consists of two or more sensors, electronic boards for processing, a telemetry (TM) package including an antenna for transmission of data, and a power supply. The most typical configuration of the yawsonde is a nose-mounted system to match a nominal artillery fuze shape. An FM/FM telemetry system transmits sensor data to a ground TM receiver. The raw data are a series of pulses (positive and negative) that measure times at which an optical sensor is aligned with the sun. These data are processed to give a solar aspect angle (Sigma-N) and the solar roll rate of the projectile. Sigma-N is defined as the magnitude of the included angle between the roll axis and the solar vector, with both beginning at the center-of-gravity of the flight vehicle (see Figure 5). The Sigma-N data contain the peak-to-peak angular motion of the projectile about the trajectory. The Sigma-N data can be further demodulated to provide the fast-mode (nutation) and slow-mode (precession) rates. The following steps are required to fabricate and test an instrumented yawsonde projectile: installation of the optical sensors within a flight vehicle, calibration, launch window simulation, flight testing, and data reduction.

A sample of yawsonde data is available for spin-stabilized projectiles. Figure 6 represents an artillery round exhibiting a nicely decaying spin history. The yaw history is typical of a spin-stabilized shell with a slight slow-mode limit cycle. Both the fast- and slow-mode motion can be observed for the artillery round.

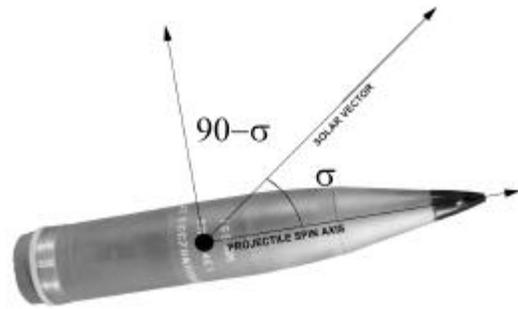
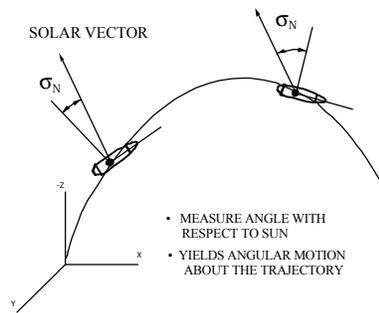


Figure 5. Depicted yawsonde measurement.

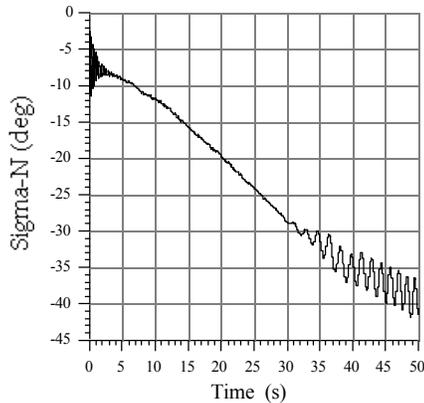


Figure 6a. Artillery flight motion.

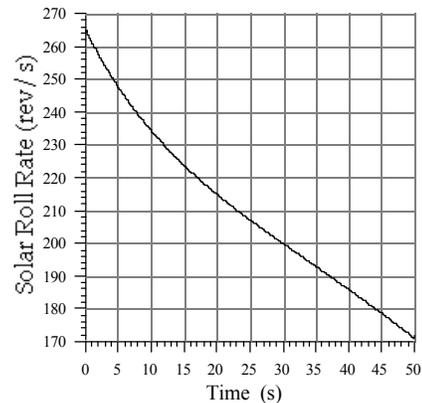


Figure 6b. Artillery solar roll rate data.

Other sensors have been flight tested in place of or in combination with the yawsonde. The g-ranges and frequency bandwidths vary depending on the application. A number of artillery projectiles and rockets were instrumented with axially oriented accelerometers (Davis 1997, Brown 1996). The accelerometer has been shown to measure the axial or radial acceleration in the presence of spin (Davis 1998). Figure 7 shows test data from an axially oriented ADXL05 on board an artillery projectile. The acceleration curve was compensated for spin-induced effects using the lab calibration information and the on-board magnetic spin sensor data. A 6-degrees-of-freedom (DOF) trajectory simulation of the accelerometer's output while on board the artillery projectile was also performed. The accelerometer's cross-axis sensitivity, misalignment, and the location away from the projectile's CG and spin axis were measured from laboratory measurements or modeled from the manufacturer's specifications. In Figure 8, the fit of the spin-compensated acceleration output was compared to a fit of Weibel radar data that had been corrected for gravity and slant range effects and to a fit of the simulated data. Very good agreement was observed. Small differences between the three were observed but were accounted for in the analysis.

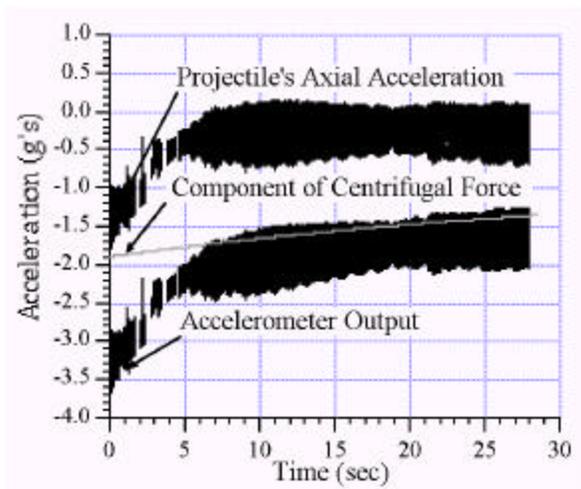


Figure 7. Axially oriented accelerometer output.

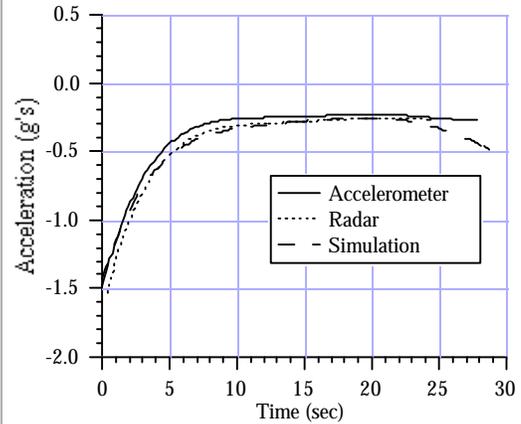


Figure 8. Accelerometer and radar comparison.

Radially oriented ADXL50 and ADXL181 accelerometers were flight tested on board artillery projectiles. Data was available at muzzle exit through ground impact. Figure 9 shows the radial acceleration from an ADXL181 in flight. The DC shape is predominantly a measure of the centrifugal acceleration as seen by the centrifugal force calculation overlaid on the accelerometer's output. After removal of the centrifugal force, the remaining oscillating part corresponded to the projectile's yawing behavior modulated near the spin frequency. The large radial acceleration amplitude near the beginning is due to tipoff.

Magnetometers have been flight-tested in munitions. The magnetometer can measure the projectile's roll rate and its yawing angle relative to the earth's magnetic field. The magnetometer requires direct exposure to magnetic field lines and must be fired along the proper firing direction relative to field lines. This reduction technique is not as accurate as the yawsonde's but offers the advantage of not having the sunshine limitation. Figure 10 shows excellent comparison to the yawsonde data.

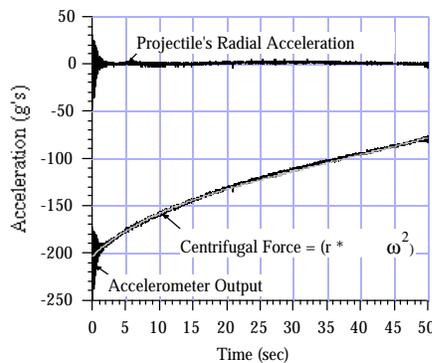


Figure 9. Radially oriented accelerometer output.

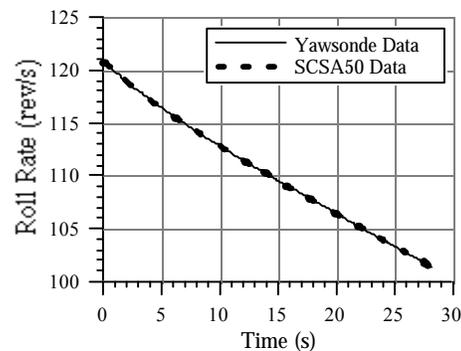


Figure 10. Magnetometer measuring artillery spin.

OBTAINING IN-FLIGHT AERODYNAMICS

The PC-YAWSONDE data reduction system is a personal-computer (PC) based program for the reduction of radar and yawsonde range data to extract aerodynamic coefficients and thrust profiles. This data processing system was developed by ARL and Arrow Tech Associates (Whyte and Mermagen 1972; Whyte and Steinhoff 1993). Experimental data from a series of trials with the 2.75-inch have been analyzed using the PC-YAWSONDE system and are used as an example (Brown et al. 1997).

The radar and yawsonde data are combined with the projectile physical data (weight, center of gravity, and moments of inertia), physical test setup data, and meteorological data. All data are combined with a 6-DOF fitting program to obtain drag and moment coefficients. Estimated aerodynamic data are used to start the fitting process. The measured roll, one-dimensional angular motion, and radial velocity data as a function of time are used to obtain a unique fit of the data, thus implying the necessary forces and moments to have caused the measured motion. From these fits, estimates of the drag, static moment, and damping moment are obtained at particular Mach numbers for the fits.

Atmospheric table computation is utilized when meteorological (MET) data as a function of altitude are not measured. Minimum requirements for the computation are Sea Level pressure (millibars), temperature (C), wind direction (degrees from north), and velocity (m/s). A 6-DOF simulation is used to simulate the motion of the initial guess aerodynamics, simulate the observed motion, and validate the yawsonde analysis process. After MET data, sun position, and initial aerodynamic profile have been entered; the range data are investigated. The radar position, with respect to the gun, is recorded to correct for any offsets (parallax errors). The spin, yawsonde data, and Doppler radar data are combined to a common time scale. From this point, a linear theory analysis is performed over the first few seconds of flight to produce a starting solution for the modified 6-DOF. The fitting of the simulated motion to the measured motion can be minimized via automatic iteration of various unknown aerodynamic coefficients. In this manner, the coefficients are manipulated to fit the measured data.

The fitted experimental data shown in Figures 11a-b is the first stage of processing. From these fits, the aerodynamic coefficients are obtained (Figures 12a-b). The quality of the match to the experimental data for these trials is 0.52 m/s for velocity, 0.50 rev/s for roll rate, and 0.14 degrees for sun angle. The limiting factor on the extent of fitting the sun-angle data was the small amplitude of the motion for much of the flight time. However, where angular motion was observed, the motion was matched and aerodynamics extracted.

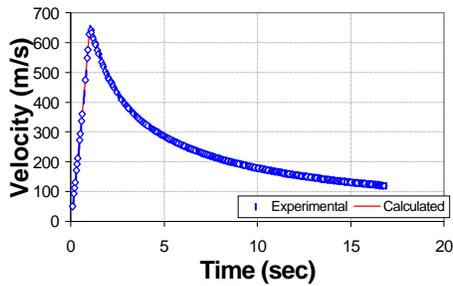


Figure 11a. Velocity vs. time.

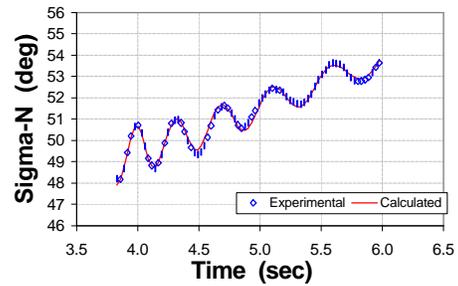


Figure 11b. Sun angle vs. time (Mach 0.5).

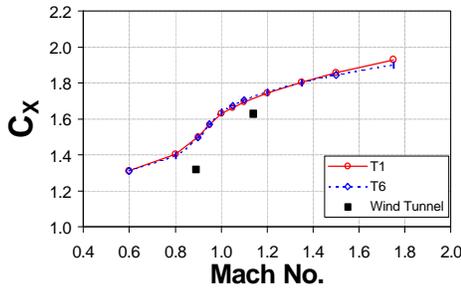


Figure 12a. Axial Force Coefficient.

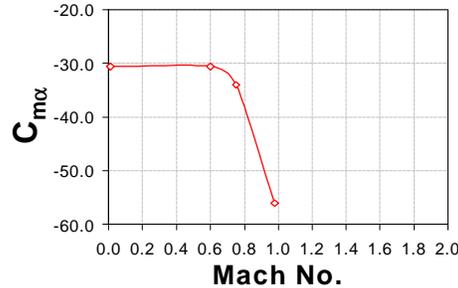


Figure 12b. Pitching Moment Coef. Derivative.

SUMMARY

Telemetry systems provide a valuable tool for flight diagnostics. A telemetry system gives a true measurement of actual flight characteristics without the influence of a sting, as in wind tunnel testing, without the expense of a time-consuming computational fluid dynamic (CFD) analysis of such a complicated geometry, and without numerous Mach number tests at indoor ranges required to define the aerodynamic characteristics over the full trajectory. This technique decreases the number of test shots required, reduces the complexity of the test setup, and reduces the test costs.

Examples have shown that telemetry packages can be placed within empty voids of the munition or in place of the fuze or warhead section while maintaining projectile characteristics. Yawsonde, accelerometer, and magnetometer sensors have been incorporated into these telemetry packages, providing in-flight acceleration, rate, and position measurements. By combining these sensor data with a 6-DOF trajectory code, many of the projectiles aerodynamic coefficients including drag, static moment, and damping moment over a large Mach number range and over multiple flight paths have been obtained.

The costs for instrumenting projectiles with telemetry systems can range from \$6,000 to \$15,000/unit depending on the sensors selected, quantity needed, and packaging requirements. This price includes fabrication and data reduction. Additional fixed costs will be charged for travel, documentation, telemetry support, and range support.

ACKNOWLEDGMENTS

This paper represents work that spans many years. The early telemetry work was initiated by members of the Ballistic Research Laboratory and has continued to evolve under members of the Army Research Laboratory as technology progresses. AMCB, led by Dr. W. D'Amico, is currently responsible for providing in-flight instrumentation and for advancing this technology. AMCB personnel from the electronics team (L. Burke, D. Hepner, and P. Muller), mechanical design and simulation team (F. Brandon, G. Brown, B. Davis, M. Hollis, J. Condon, T. Harkins, A. Thompson, and V. Lietzke), contractor support staff (E. Irwin, C. Myers, C. Mitchell, W. Clay, A. Keller, and E. Edwards), and branch secretary (B.J. Acker) have contributed to this paper at some level through their dedicated work. Ron Colangelo, PM STRICOM, is acknowledged for funding many of the high-g ground tests and flight demonstrations under the HSTSS program.

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