

Health Monitor System for Damage Assessment of Military Assets

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Abstract

Military equipment is exposed to different types of mechanical stresses during various portions of their life cycles. Personnel handling, transportation, storage, and deployment can expose equipment to high levels of shock during inadvertent drops or collisions. Truck, airplane, and helicopter transport exposes equipment to moderate levels of vibration at many different resonant frequencies. Rapid temperature excursions can generate thermal stresses due to variations in material thermal expansion coefficients. Even though delicate components are usually placed in robust containers with shock damping features, most systems are susceptible to shock damage at some level. To address this vulnerability, engineers at the Battelle Pacific Northwest Division have developed a family of asset Health Monitors to determine when military assets have been exposed to environmental stress in excess of their design envelopes. The concept is embodied in a low cost, low power, battery powered Health Monitor mounted to the asset that is capable of measuring, recording, and analyzing mechanical shock and temperature excursions. By storing data along with a time stamp, the Health Monitor can be used to determine equipment readiness, flag potentially damaged equipment, and trace the root cause of equipment malfunction. The system concept includes a printed circuit board, temperature sensor, a tri-axial accelerometer, batteries, push buttons, and status indication lights. When a temperature or shock level is higher than a predefined threshold, an alarm light will be displayed when the health monitor status is evaluated. This paper will describe the overall system design, system components, energy conservation techniques, and concept of operations.

Key Words: health monitoring, sensors, structural response, smart structures

Introduction

For remote systems deployed in hazardous environments, a severe shock event can occur at any time. Personnel handling, transportation, storage, and deployment can expose equipment to high levels of shock during inadvertent drops or collisions. Even though delicate components are usually placed in robust containers with shock damping features, most fielded systems are susceptible to shock damage. To address this need, engineers at Battelle Pacific Northwest Division have developed a family of asset Health Monitors to detect if and when assets have been subjected to shock in excess of their design envelopes. The concept is embodied in a low cost, low power, battery operated Health Monitor that is either mounted to the asset or mounted to its shipping container. By capturing shock data along with a time stamp, the Health Monitor can be used to determine equipment readiness, flag potentially damaged

equipment, and trace the root cause of equipment malfunction. This paper focuses on a Health Monitor that was developed for a man-portable missile container.

Asset impact indicators have been used for many years to identify shipments that have been subjected high level shock during transportation. Commercial impact indicators are available that provide a visual indication (e.g. red dye inside a ruptured clear vial) if the device has been subjected to an impact exceeding a specified shock level. Electrical component indicators rely on the change of state of an electrical component to indicate a high shock event has occurred. For example, shock acceleration switches have been developed that activate when a threshold shock has been detected [1]. Early approaches in impact detection incorporated small electronic packages with onboard

microprocessors. Rudimentary signal analysis techniques, such as comparing the maximum shock or strain during an event to a predefined threshold, were used to signal an alarm condition. Because the threshold could be reset and the date and time of the event could also be recorded, these devices were more flexible and could provide enough information to deduce the time, location, and cause of the shock event. Recently, civil structures have been instrumented with a large number of shock sensing units that can transmit data through a wireless sensing network to a centralized data storage computer [2]. With spatially resolved data, this type system is capable of computing modal frequencies, shapes, and damping ratios. Damage identification methods based on changes in vibration mode shapes have encountered some success [3].

The Health Monitor System differs from existing impact indicators because it uses shock data along with an analysis algorithm to estimate the drop height. Since most military assets are designed to withstand a maximum drop height, rather than a maximum shock level, knowing when the asset has been dropped from a height greater than the design limit is important to assess the functional readiness of the asset. The system is self contained and can assess shock events autonomously.

System Overview

The Non-Line of Sight Launch System (NLOS-LS) is a family of artillery missiles fired from a vertical launcher that can be deployed by ground or air assets and networked to quickly engage an enemy. NLOS-LS is being developed by the NetFires LLC, which is a partnership between Raytheon Missile Systems (RMS) and Lockheed Martin. A Health Monitor System (HMS) will be mounted to the aft end of each missile container. The HMS was developed by Battelle through a subcontract with RMS. The HMS is a low-cost, lightweight, autonomous, and self-powered electronic system capable of measuring, recording, and displaying key status information that enable the soldier to ascertain if the NLOS-LS missile container has been subjected to environments that could have caused damage to the missile. Health status is displayed in an easily discernable, "go/no-go" manner upon activation of the status lights. The three critical parameters are external shock, temperature to which the container has been exposed, and internal container humidity. The physical size of the HMS is approximately $2.5 \times 2.5 \times 1.7$ inches (Figure 1) and the weight is approximately 5 ounces. The HMS includes a printed circuit board, humidity sensor, temperature

sensor, a tri-axial accelerometer, batteries, push buttons, and status indication lights.



Figure 1. Photographs of Health Monitor System

Equipment shock limits are usually specified in terms of maximum shock level or maximum drop height, and both of these limits have been employed on Health Monitors. Applying the maximum shock level criteria may be appropriate for assets with a known fragility level, whereas applying the maximum drop height criteria may be appropriate when the Health Monitor is attached to the shipping container, as is the case for the NLOS-LS missile container. Assessing drop height from shock data is complicated by the fact that containers are three dimensional systems with different impact surfaces (corners, edges, and flat surfaces). The container impact surface can significantly affect the shock amplitude and frequency response of the container during a drop. For the NLOS-LS program, an analysis algorithm was developed to determine drop height from a variety of drop orientations using shock data from a MEMS 3-axis accelerometer. When a shock event is higher than a defined threshold, an alarm light will be displayed when the HMS status is queried. The algorithm has been successfully implemented as firmware running on the Health Monitor microprocessor.

On Board Sensors

The HMS employs an array of sensors to characterize environmental exposures, including temperature, humidity, and shock, to the system of interest. The HMS analyzes acquired data to determine if a potentially damaging exposure has taken place. The HMS is able to acquire data from the sensors on a set timetable or, in the case of shock data, after a threshold has been exceeded. Temperature and humidity are recorded on an hourly basis, allowing the daily temperature and humidity cycles to be observed. The shock sensor has an activation threshold and, once that threshold is exceeded, the HMS will record the shock data. Specifics of the HMS and sensor data acquisition are discussed in the following sections.

The temperature sensor is the Model LM94021 from National Semiconductor. It is accurate to $\pm 2^{\circ}\text{C}$ over a temperature range of -50°C to $+150^{\circ}\text{C}$ and has a low supply current of $9\text{ }\mu\text{A}$. To further reduce the power consumption of the temperature sensor, it is powered on only when a measurement is needed.

The humidity sensor is the Model SHT75 from Sensirion. It is accurate to $\pm 1.8\%$ relative humidity (RH) from 10% to 90% RH. Sensor accuracy from 0 to 10% RH and 90 to 100% RH is to $\pm 4\%$. This capacitive humidity sensor has a low supply current of $2\text{ }\mu\text{A}$. The humidity sensor performance has been stable during extreme temperature and humidity exposures.

The shock sensor used in this design is the Model H48M from Hitachi Metals, with a designed shock range of $\pm 50\text{ g}$ ($1\text{ g} = 9.81\text{ m/s}^2$). The sensor is a piezo ceramic accelerometer with a package size of $4.8 \times 4.8 \times 1.25\text{ mm}$. Because this sensor is purely resistive, the current consumption and measurement sensitivity is directly proportional to the supply voltage. The shock sensor is required to be powered on at all times. With a standard supply voltage of 2-5 volts, the current consumption was too significant to allow the sensor to be continuously powered. The solution was to lower the supply voltage significantly, which then required the output signal to be amplified. A dual-stage amplification circuit was used to amplify the sensor output signal. This allowed the sensor and the required circuitry to operate at $33\text{ }\mu\text{A}$. Because the shock sensor is required to be powered on at all times, its current consumption causes the largest drain on the HMS battery.

The shock monitoring circuitry is always on, allowing the HMS to record a shock event in any of the axes. To reduce power consumption, the microcontroller is usually unpowered. When a shock event occurs and a programmed threshold is exceeded, the microcontroller turns on to record the waveform. The microcontroller turns on within $11\text{ }\mu\text{s}$ after a threshold has been exceeded. This minor loss in data is negligible and does not affect the accuracy of the shock data and analysis, since the shock events were typically $8000\text{ }\mu\text{s}$ in duration. Once the microcontroller begins to record the data, it records the x-axis, then $24\text{ }\mu\text{s}$ later the y-axis, then $24\text{ }\mu\text{s}$ later the z-axis. It then repeats this cycle starting with the x-axis. The 3-axis measurement results in a $72\text{-}\mu\text{s}$ sample period. The HMS is set to record 256 points per shock event. Recording 256 points has been determined through analysis and testing to be long enough to capture the entirety of an expected shock event.

The shock circuitry must operate over a large temperature range of -55°C to $+78^{\circ}\text{C}$. The shock sensor is resistive, and its sensitivity varies with changes in temperature. The shock measurements are adjusted to compensate for the effect of temperature. A temperature chamber with drop apparatus was used to determine the correlation between temperature and shock sensor sensitivity. Testing showed that sensor sensitivity is linearly proportional to the change in temperature. Adjusting for sensor temperature sensitivity allows for the most accurate measurements.

The shock sensor was specified to work for the range of $\pm 50\text{ g}$. The HMS is required to measure $\pm 200\text{ g}$. Testing showed that the sensor could function properly over a shock range of $\pm 300\text{ g}$ with minimum loss of accuracy. The sensor is not damaged by operating outside its specified range because it has a damage tolerance of $\pm 5000\text{ g}$. Trade studies showed no alternative accelerometer option that was low power and had high shock measurement range. A key feature of the HMS is its ability to measure and record a shock event using a single-point 3-axis accelerometer. Proving the function and design of the HMS shock analysis required extensive testing, which is described later in this paper.

In a relatively small package, the HMS incorporates an extensive array of electronic sensors to monitor many environmental stresses and exposures.

HMS Electronic Design

The HMS electronic design was created to measure, record, and analyze data for more than 10 years. The electronic design requires low-power circuitry and sensors to meet the required lifetime of 10 years without a battery replacement. A low-power microcontroller from Texas Instruments is at the center of the electronic design. The microcontroller acquires, records, and analyzes the data from the sensors. The sensors incorporated into the HMS are low power or have been adapted to maintain functionality with lower power. To maintain a low-power design, the components and sensors not in use are put in a low-power mode or turned off completely. Figure 2 provides a functional block diagram of the HMS electronic design.

Drop Test Methodology

Extensive drop testing was completed with the HMS to develop and enhance the drop algorithm. The following sections will discuss the testing, modeling and implementation of the HMS drop algorithm. The HMS is mounted to a container that will be manually manipulated during transport and

deployment. The operational scenario was analyzed to determine potential circumstances in which the container would be unintentionally dropped, which led to the development of seven distinct drop orientations as shown in Figure 3. Six of the drops are pivot drops, in which one end of the container is propped on a rigid surface and the other end is allowed to fall in a rotational manner. The initial orientation of the container was constrained to allow the impact surface to be on the bottom of the container opposite the handles. The impact surface was either a flat edge or one of the two bottom corners, resulting in a total of three pivot drops on the aft end and three pivot drops on the forward end. The final type of drop was a vertical drop onto the bottom edge of the aft end. In this type of drop, which might occur during installation of the container, the center of gravity of the container is vertically aligned with the bottom edge of the container.

As shown in Figure 3, the HMS is mounted to the aft end of the container. The x-axis of the HMS accelerometer is aligned with the vertical direction of the container, the y-axis is aligned with the lateral direction, and the z-axis is aligned with the longitudinal direction.

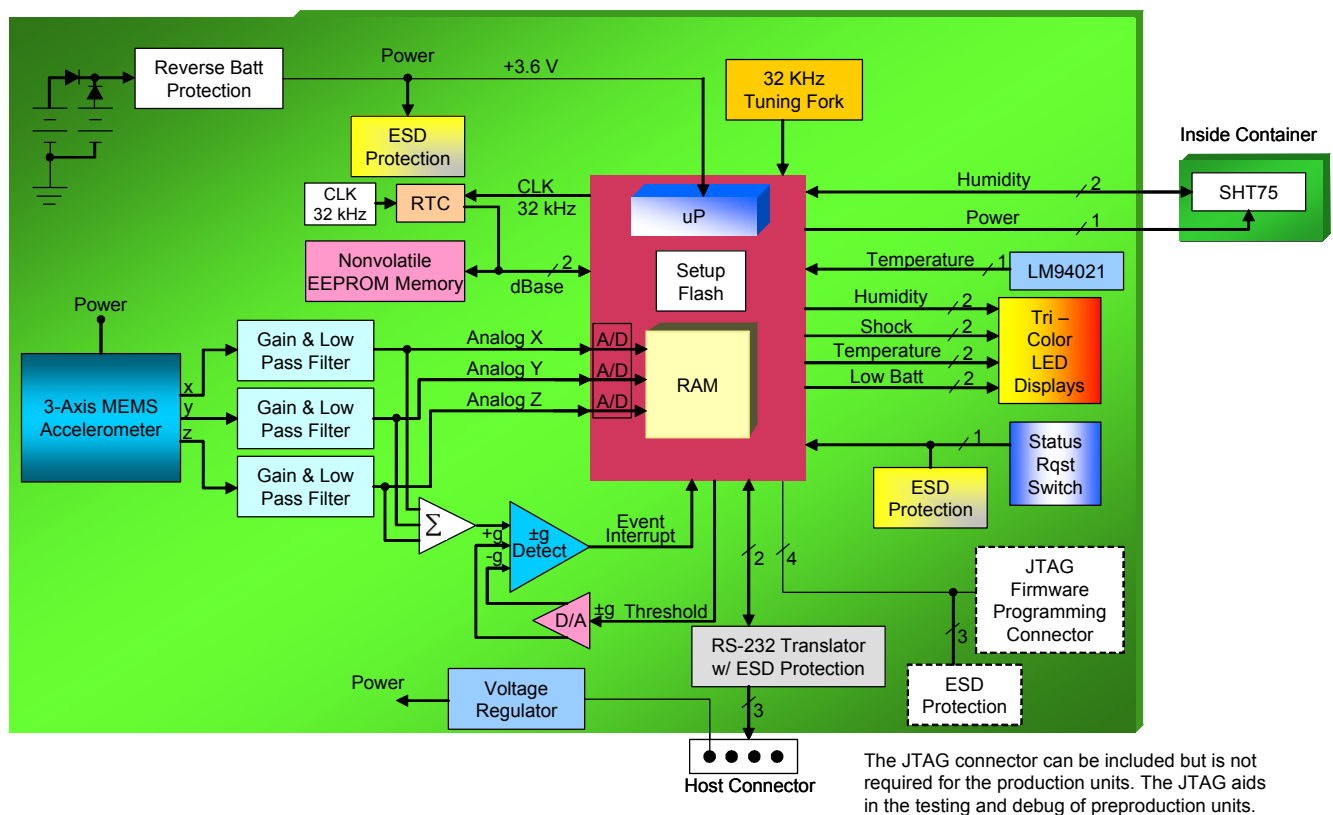


Figure 2. HMS Electronics Functional Block Diagram

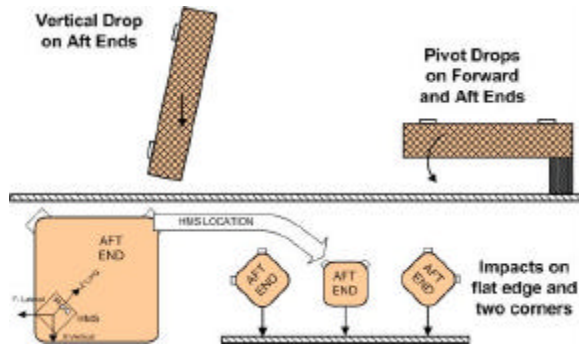


Figure 3. Container Drop Orientations

For a simple one dimension spring/mass system, drop height, impact velocity, and impact shock are related by the following equations:

$$\Delta v = \sqrt{2 \cdot g \cdot h} \quad (1)$$

$$\Delta p = m \Delta v = \int F \cdot dt \quad (2)$$

$$\Delta v = \int \ddot{x} \cdot dt \quad (3)$$

$$\int \ddot{x} \cdot dt \approx \sqrt{2 \cdot g \cdot h} \quad (4)$$

Where:

Δv =	impact velocity
h =	drop height
g =	acceleration due to gravity
p =	momentum
m =	mass
F =	deceleration force
$\ddot{x}$ =	deceleration
t =	time

These relationships have been used to calibrate accelerometers using a ballistic pendulum [4]. Here, it was observed that the area under the accelerometer output curve can be used, in conjunction with a known drop height, to experimentally determine the calibration factor. For the NLOS container, the calibration factor of the accelerometer and the integral of acceleration can be used to estimate the drop height. Even though the NLOS container is a three dimensional system, it was expected that this basic theory could be used to develop a correlation between drop height and shock.

Shock Assessment Algorithm

Early in the development of the HMS shock measurement feature, it became evident that a fairly

sophisticated approach was needed to assess drop height from shock measurements. The development of the algorithm is a consequence of the complications resulting from the fact that the container is a three-dimensional system with flat edges and round corners and that the HMS is able to measure shock only on the aft end. Significant testing was conducted to develop a methodology for using HMS shock data to determine if the container has been dropped from a height greater than 18 inches from different drop orientations. The major advances achieved in the development of the shock algorithm are described below.

Maximum shock levels are sensitive to container impact surface. Also, drops onto the corner of the container result in much lower maximum shock levels than drops onto the flat edge from the same height. By integrating the first half period of acceleration, a measure of the energy required to bring the container to rest is obtained that is directly related to drop height.

Each shock type can pose a different damage to the asset and because of the varying nature of each event the ability to apply individual alarm thresholds to each shock type is crucial. Furthermore, due to the location of the HMS on the aft end of the container, the shock response measured from drops on the forward end is much less than shock response measured from drops on the aft end. Digital logic involving the direction (sign) of the shock response was used to determine if the container has been dropped on the aft or forward end. A different threshold is applied, depending on if the drop was on the forward or aft end.

In summary, the algorithm involves capturing raw shock response data and then integrating the first half period to arrive at an energy-based shock parameter. The impulse energy from the X and Y channels are summed vectorially to account for the fact that the container could be dropped on the flat edge or corner. Finally, the measured impulse energies are compared with pre-established energy thresholds to determine if the drop was at a height greater than 18 inches. A final complication results from the fact that pivot drops on the forward end lead to lower shock levels measured at the aft end, where the HMS is mounted. To account for this, the HMS uses a lower threshold when the direction of the shock indicates a drop on the forward end.

Test Setup

An asset mass/inertia simulator was installed on a tactical container. All drops were onto an

undamaged portion of 1-inch-thick plywood, which was intended to replicate the impact response of compacted earth. Dropping onto plywood also reduced the effect of variations in compactness and consistency that might be introduced by using actual soil. For pivot drops, the fixed end was supported by a rigid base; a small rubber pad was placed between the container and the base. To test at high and low temperatures, the container was placed in a temperature enclosure and allowed to equilibrate. After the container had been at the desired temperature for 1 hour, the temperature enclosure was removed and the container was dropped.

During the drop tests, the HMS was in the tactical configuration and collected the data autonomously. The HMS was set to record the shock impulse with a trigger threshold of 9 g. After the HMS was triggered by an event, it recorded the waveform at a sample rate of 72 microseconds for a period of 256 samples per axis. After the HMS collected the shock data, it could be downloaded to a computer to further analyze the shock event. The HMS download program was enhanced so that drop test data could be uploaded into the HMS memory and then analyzed. Using this process, test engineers verified HMS functions for analyzing the shock data, integrating the response, distinguishing drop orientation, and applying the appropriate threshold. By using off-line code validation, Battelle engineers were able to debug and validate the firmware prior to testing.

The shock response from pivot drops on the aft end of a container prototype is plotted against drop height in Figure 4. The area between the shock response and the time axis for the first $\frac{1}{2}$ cycle is plotted against drop height in Figure 5. Note that Figure 5 includes a large number of data points from repeated drops at the same height. A power law curve was fit through this data and is shown in Figure 5 as a curve through the data points. For these drops, the power factor was 0.73, which is relatively close to the 0.5 power that was predicted in by Equation (4).

Conclusion

Drop testing and statistical analysis confirmed that the Health Monitor System could accurately capture maximum shock levels and estimate drop height from all required drop orientations. Although alarm status is available on request from the HMS, detailed data can be downloaded to handheld computers for analysis. Variations of the Health Monitor System have been designed by Battelle for military applications on supply pallets, portable missile containers, and control systems.

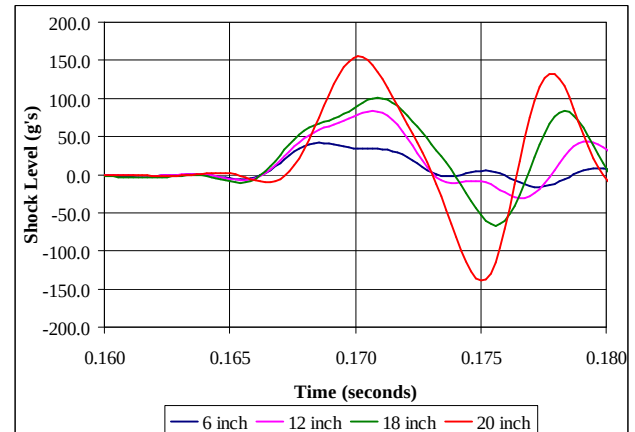


Figure 4. Shock Response versus Time for Drop Heights of 6, 12, 18, and 20 inches

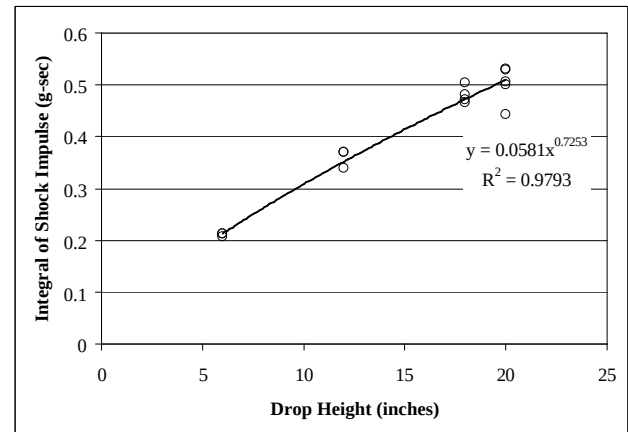


Figure 5. Integrated Shock Response versus Drop Height

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