Instrumentation for Impact Analysis

Abstract

A test apparatus and appropriate instrumentation were designed by a student with the help of a faculty, to test the deceleration time of a specified impact force applied to a test subject. The apparatus was made to be adaptable to different configuration requirements of future research. This apparatus utilized the accelerating force of gravity in a procedure known as “drop testing”, in which the test subject is placed at the base of the apparatus. A measured mass is then raised to a calculated height, where the potential energy is released as the mass is guided along a path to impact the test subject. An accelerometer was used to indicate the velocity and deceleration time, to verify the impact force, and calculate the impact rating of the test subject.

The data was converted into useful graphs of acceleration, force, velocity, and position in respect to time. The accelerometer contained an internal voltage regulator and an oscillator and produced a signal that was modulated to represent the acceleration experienced by the accelerometer.

The data from the procedure was stored electronically for calculations, analysis, and documentation. Results of the experimentation provided much insight into the varying characteristics of different materials to absorb the energy of physical impact. The paper will discuss the design process, the instrumentation involved, and the results of the tests as well as related student learning.

Introduction

The researchers were tasked with creating a method of determining the mechanical characteristics of various materials used in sports protective gear, particularly mouthpieces. A notable corporate sponsor approached the university about conducted related research. Faculty, facilities, and a graduate student were identified and put in place to accomplish the requested goals. Unfortunately, at the onset of the economic downturn, the company withdrew its support. By this time, the interested faculty and student had already identified the needed apparatus and methodologies. Existing instrumentation was identified to perform the task, as well as a minimal amount of budget reserves to purchase ancillary items. The test apparatus design was modified to fit the existing instrumentation and available resources.

Test Apparatus

The apparatus used was designed to utilize gravitational acceleration for consistent and repeatable results. Several differing configurations were considered throughout the design and even construction process. The final arrangement made use of two angle bars as guides for a solid rectangular mass, as shown in Figure 1. The mass can be freely lifted vertically along the guide rails to max height difference of 87.6 cm (34.5 in). The rigidity of the structure is maintained by two supports of metal plumbing pipe bolted to the base and top of the front half of the structure. The back part of the structure is bolted directly to a concrete wall. The base of the
structure uses an optical table for its rigidity, consistency, ease of positioning, and versatility. The impact surface is a machined block of aluminum similar to the drop mass. A small block of wood is placed between the mass and the impact surface to protect the integrity of the impact zone while not in use. The guide rails are held to the block and the top via angle brackets. Counter sunk bolts connect the brackets to the rails without impeding the fall of the mass. The top is constructed from wood and is used as a shelf to house much of the required instrumentation.

Sensors and Instrumentation

A capacitive accelerometer was implemented as part of the instrumentation to measure the acceleration of the mass though its fall and immediately after. Capacitive accelerometers utilize the changing distance between its plates to generate an electrical signal that is proportional to the applied acceleration. Given a known seismic mass of an accelerometer, it actually provides an indication of the force incumbent on the accelerometer, which is proportional to the acceleration through Newton’s second law

\[ F = ma \]

Since the internal structure of the accelerometer is that of a variable capacitor, force on the device causes the mass to move a distance closer to one electrode, equal but opposite to the distance from the opposing electrode. A diagram of the sensor is shown in Figure 2 in a “0 g” state and in Figure 3 in a “+1 g” state. The distance (x) moved is not only a function of the applied force, but also the spring constant (k) as in Hooke’s Law defined as

\[ F = -kx \]

The change in capacitance that results from the change in plate distance is given by

\[ C_1 = \frac{A \varepsilon}{d \pm x} \]
Where \( C \) is capacitance, \( A \) is electrode area, \( d \) is distance between mass and electrode, and \( x \) is displacement of the mass. The physical properties of the accelerometer included sensitivity of 102 mV/(m/s\(^2\)), a frequency range of 0 to 100 Hz, and a 10 Hz phase response of under 3\(^\circ\).

The accelerometer contains a voltage regulator integrated within its structure. This allows for external power to be supplied by any source within the 10 to 30 VDC excitation range. The change in capacitance is detected by a capacitance bridge where each arm of the bridge functions as a capacitance divider. The outputs of the bridge are then amplitude modulated signals that are directly proportional to the changes in capacitance. A series of diodes and capacitors within the accelerometer are used to demodulate the signals which are then summed, amplified, and filtered to provide a voltage signal that is proportional to the acceleration.

The accelerometer is adhered to the top of the mass so that it can measure its movement as it impacts the test subject, as shown in Figure 4. Wires from the accelerometer are positioned free to move as not to obstruct the freefall of the object. This unobstructed movement is accomplished by tethering the wires to a block positioned at the midpoint of the accelerometers range of motion and ultimately connects to the power supply and the data acquisition module through a series of wiring terminal blocks. The collected data was then subsequently graphed as acceleration, force, velocity, and position in respect to time.

The output of the accelerometer is passed to a data acquisition module. The module is designed to take analog voltages from instrumentation and perform analog to digital conversion. The converter used in this case provides wire terminals for the analog signals and a USB connector for connection to a computer. The digital information available at the USB port is thus transferred to a computer.

A computer with virtual instrumentation software was used to acquire the digital data and display pertinent values on the screen. A graphical user interface, as shown in Figure 5, was developed to display this data, as well as providing operator control of testing, such as starting and stopping the data collection, and calculating the drop elevation for a desired impact force.

**Test Procedure**

The response to mechanical force impacted on a mouthpiece material was induced by impacting it with a direct force of 200 N. The measurement of the deceleration of the impacting mass upon the material may then be used to provide an indication of the protection provided by the material. Through this method of impact testing, various materials could be consistently characterized and ranked for their relative protective capabilities.
The accelerometer requires approximately fifteen minutes for orientation before a critical measurement. A timer was built into the data collection program to easily ensure that this time constraint is followed. The program also calculates the height to raise the impacting mass to achieve a desired force over a measured object.

Due to its extreme sensitivity, the accelerometer is vulnerable to a discernible amount of noise. This noise can greatly influence the measured results over time. The program adjusts to filter this noise while the graphs are not running. The specifics of how this is done without altering the data are discussed under Data Collection and Analysis. Before conducting the experiment, the established procedure allows the program to adjust for noise by ensuring the graphs are not running before starting the program.

Procedurally, the operator of the experiment must first raise the mass to height as specified by the program. The height is displayed once the user enters desired impact force in Newtons. The graphs are then initiated to establish baseline reference. The operator then ensures that all graphs are reading as expected and before releasing the mass. After the impact, all graphs are turned off, and the program stopped, thus completing the test.
Data Collection and Analysis

The accelerometer transmits data as a varying dc waveform, and inherent noise in the signal can alter reliability of the data. All mathematical alterations of the signal stream were performed within the virtual instrumentation software. To filter the noise, the signal is first averaged over time. When the graphs are started the averaging stops and locks the current average into a variable. The previous average is then subtracted from current signal. This quickly and easily eliminates much of the noise and the offset due to gravity, but a constant signal of zero has not yet been achieved. Now the program passes the signal through a comparator. If the absolute value of the new average of the signal over time is less than .02V then it is removed completely, eliminating noise while not affecting the experiment.

The signal is then divided by the sensitivity of the accelerometer to determine acceleration. This acceleration can now be multiplied by the mass given previously to calculate height. The velocity is derived by taking the integral of acceleration. Position is derived by taking the integral of velocity. The program is designed to do all mathematical functions automatically, as well as save each experiment’s data to a separate spread sheet file.

Results

Initial testing consisted of two samples that were tested three times each. Both samples were cut from the same material for proof of consistency. The samples were made of ethylene vinyl acetate, the copolymer of ethylene and vinyl acetate, a common material used in sports mouthpieces and other protective equipment. The width of each sample was measured after each test run, as shown in Table 1.

Table 1. Calculated Deceleration Distance

<table>
<thead>
<tr>
<th>Test Run</th>
<th>Sample 1</th>
<th>Sample 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Test</td>
<td>0.365cm</td>
<td>0.365cm</td>
</tr>
<tr>
<td>Test 1</td>
<td>0.360cm</td>
<td>0.360cm</td>
</tr>
<tr>
<td>Test 2</td>
<td>0.355cm</td>
<td>0.355cm</td>
</tr>
<tr>
<td>Test 3</td>
<td>0.350cm</td>
<td>0.350cm</td>
</tr>
</tbody>
</table>

The sample width represents the hypothetical deceleration distance that can be experienced by the impacting mass. Therefore this number was used to calculate the height required to lift the mass to achieve a desired impact force of 200N. Since the width in practice never approaches zero, the use of the full width results in a resultant impact force that is slightly higher than that calculated.

Data from each test run on each sample were recorded and subsequently plotted, as shown in Figures 6 through 11. The graphs are plotted in the dependent variable force (Newtons) vs. the independent variable time (sec).
Figure 6. Impact Force of Sample 1 Test 1

Figure 7. Impact Force of Sample 1 Test 2

Figure 8. Impact Force of Sample 1 Test 3
Figure 9. Impact Force of Sample 2 Test 1

Figure 10. Impact Force of Sample 2 Test 2

Figure 11. Impact Force of Sample 2 Test 3
Each graph contains three bursts of amplitude over time, as well as minor ringing before and after. The first burst on each graph represents the initial impact. Following bursts represent rebound forces resulting from impact, or bouncing. Variances in time as displayed on the individual graphs are the result of human variability in releasing the falling mass relevant to the starting of the data collection, and are inconsequential. Peak force from each impact test is shown in Table 2.

### Table 2. Measured Force from Impact Tests

<table>
<thead>
<tr>
<th>Test Run</th>
<th>Sample 1</th>
<th>Sample 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>282 N</td>
<td>296 N</td>
</tr>
<tr>
<td>Test 2</td>
<td>295 N</td>
<td>287 N</td>
</tr>
<tr>
<td>Test 3</td>
<td>294 N</td>
<td>290 N</td>
</tr>
<tr>
<td>Average</td>
<td>291 N</td>
<td>291 N</td>
</tr>
</tbody>
</table>

Data for sample one indicates that each measurement is within xx% of the average for that sample. Furthermore, two samples of the same material demonstrated similar characteristics. Variances can be attributed to human error in positioning of the elevated mass before releasing for impact.

**Student Learning**

A first-semester graduate student was assigned to the project for the purposes of acquainting the student with instrumentation and computer hardware. The student’s undergraduate background was computer science, so he had little to no actual hardware experience. Furthermore, the student had never been exposed to experimental research. Fortunately, the student put forth the effort to learn the necessary components related to the research, and successfully completed the project. Feedback from the student indicated that he not only learned from this project, but the project also helped him understand and related unfamiliar subjects he was currently taking that semester. On many occasions, the student would bring other students into the lab to show them what he had accomplished and this exposed other student to experimental research and a learning process different from traditional classes.

**Conclusions**

The research project began with high expectations and an anticipated high level of support. Although all support was retracted, the project continued with minimal resources. Various aspects of the project, such as automated mass positioning, were scrapped, in favor of manual methods. The test apparatus proved to be sturdy and dependable, even though it was constructed out of scrap materials and minimal purchases from the local hardware store. Fortunately, the research group had need instrumentation within the lab to complete the fabrication of a working test apparatus.

Results of initial testing were positive, and the testing demonstrated reasonable repeatability of measurement. Surprisingly, the test configuration as designed requires human interaction, but
the effect of such on the results appears to be minimized. More tests were conducted and very similar results were obtained repeatedly.

Improvements to the test fixture could be made, should funding become available. Primarily, the positioning of the mass could be automated, such that the mass could be placed at a specified height with a known level of accuracy. For example, the mass could be integrated to a vertical positioning table to provide positioning within 0.001 of an inch. Relevant to the original research, a force sensor could be placed beneath the test material on the subsurface, to provide an indication of shock, transmitted force, and an indication of energy dissipated by the material.

The effects on the graduate student engaged in the project appeared to be the most beneficial outcome. Overall, the student learning component of the project was a success, and the excited student subsequently disseminated his learning outcomes and excitement to other students.

Bibliography