

SUDDEN IMPACT: DEVELOPING A MECHANICAL ACCELEROMETER USING RAPID PROTOTYPING

Patricia K. Krugjohn
Department of Mechanical Engineering
South Dakota School of Mines and Technology
501 East Saint Joseph Street
Rapid City, SD 57701. USA

Rapid Prototyping Center
Milwaukee School Of Engineering
1025 North Broadway
Milwaukee, Wisconsin 53202. USA

Faculty Advisor: Dr. Larry Fennigkoh

Abstract

An accelerometer is a device that measures acceleration. Most accelerometers are electrical. A transducer experiences acceleration and converts it into a signal that measures the acceleration. A device such as this requires a power source and conditioning electronics, complicating certain applications. This project proposes developing a self-contained, mechanical accelerometer, initially as a single axis device. The device incorporates the use of a spring-mass system. A given mass is displaced by an applied acceleration, that displacement recorded by a system of ratcheting teeth. Through the displacement acceleration is found. The method by which the displacement is recorded is easily reset, enabling repeated use. Rapid prototyping was implemented in order to prototype a model. This is due to the precision achieved using rapid prototyping, and the speed with which a prototype is produced. Once a model was completed it was calibrated using a centrifuge. Several different springs and masses were used in order to discover which combination of spring and mass would achieve the optimal range of accelerations that the device would be capable of reading. Upon completion of a successfully modeled single axis accelerometer, conversion into a triple axis device will be possible.

Keywords: Accelerometer, Mechanical, Rapid Prototyping

1. Introduction

At present, accelerometer technology is excellent, however these accurate and highly specialized technologies have great limitations in their applications due to their electrical designs. The applications of an accelerometer could be limitless, if the design could be simplified to exclude the extra electronics and necessary power source. The development of a purely self-contained and mechanical accelerometer capable of recording acceleration would eliminate these hurdles, enabling applications that are not possible with present technology. A mechanical accelerometer would also be less expensive than the present technologies, most of which are electrical or microelectromechanical (MEMS). It is important to realize that mechanical accelerometers have been designed and marketed, however these previous designs have had no mechanism with which to record the acceleration. [1] This design proposes not only the manufacture of a self-contained mechanical accelerometer, but one also capable of logging the accelerations experienced by the device.

The Rapid Prototyping (RP) process is particularly useful in the development of a new product, such as a mechanical accelerometer. The RP process enables a very brief prototyping phase, and allows for early testing of an innovative concept. That has not always been possible. Most of the RP machines are capable of extremely precise builds, which include small parts and specific geometries. The RP process also enables the manufacture of very unique parts that would otherwise be difficult to fabricate.

2. Objectives

2.1 project criteria

There are several criteria to meet in the design of this device. Primarily, no electronics would be employed. A form of Rapid Prototyping was required to create a design prototype. The accelerometer must be entirely self-contained, passive, mechanical in design, and capable of recording the given acceleration that the system experiences. More specifically, the system must also include some mass, able to move about. It is through the displacement of this mass that the acceleration can be known. The purpose of this accelerometer device is to measure only the peak acceleration experienced by a given object. Some form of a reset mechanism is needed to allow for multiple uses of the system. Initially the accelerometer design will be single axis. Once a single axis device is successfully modeled, it could then be converted into a double or triple axis device.

2.2 goals

The primary goal was to develop a single axis accelerometer, which employs a given mass capable of a displacement. In particular, a spring-mass system was used in order to achieve this goal. The spring limits the displacement of the mass, and prevents compound acceleration readings from being taken. The incorporation of a spring and mass could be achieved in a variety of different configurations. Realizing the relationship that will attain optimal dimensions and cost parameters is an important aspect in the product development process. However, this is simply the design phase, not manufacturing, so some of these factors, specifically cost, can be ignored for the time being.

3. Rapid Prototyping/Stereolithography Apparatus

The Stereolithography Apparatus (SLA) is among the top Rapid Prototyping technologies available. The process builds a computer aided drafting (CAD) file in layers, utilizing an ultraviolet laser beam and a tank of liquid photopolymer (epoxy resin). Before a build begins, a support structure is built onto the platform; this makes it easier to remove the part from the platform post-production. The laser traces the shape of the part from a CAD file, as one layer is completed the platform is lowered and the next layer is traced by the laser. (Figure 1) As the laser traces the pattern, the liquid photopolymer cures, allowing the next layer to be completed. Once the entire part has been completed, the platform raises out of the liquid bath, allowing the part to be removed.

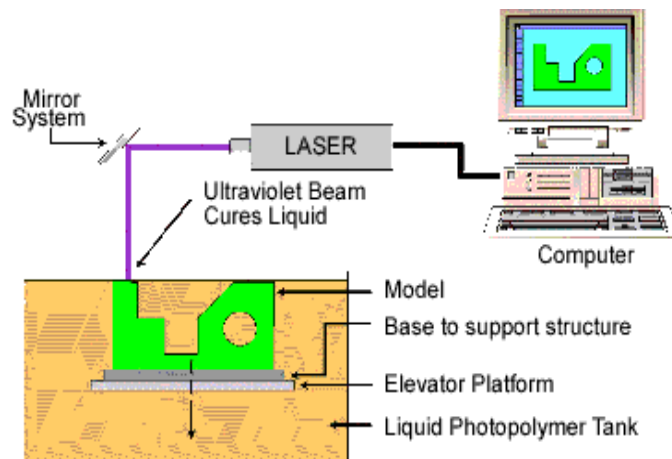


Figure 1. The Stereolithography Apparatus process [2]

This particular process was well suited to the desired prototyping process for the mechanical accelerometer device. The design of the device is relatively small, a matter of centimeters in length. There are precise details that must be produced to enable the recording of displacement. Overall, the SLA material has properties conducive to those

required in the accelerometer design. The SLA also has capabilities that enabled a small period for prototyping, allowing for a longer testing period.

4. Design

The design shown below (Figure 2) is of the casing for the spring-mass system. The thought behind this design is that the bottom may be removed allowing for the spring and mass to be interchanged with other springs of different stiffnesses, and varying masses. This aspect of the design was specifically incorporated for the testing phase. Should one combination of spring and mass not function as desired, another combination can be tested. In this way the optimal combination of spring and mass can be achieved for the system.

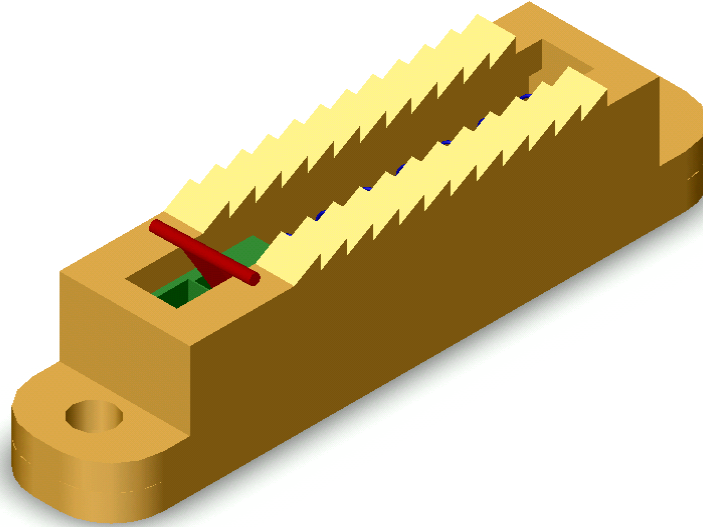


Figure 2. SolidWorks® Assembly of Mechanical Accelerometer Design

The spring-mass system shown above (Figure 2) satisfies the need to record displacement, via the implementation of the angled ratcheting teeth shown above. The ratcheting effect that these teeth have on the measurement device will serve to record the displacement induced by the mass. Within the device a compression spring, a mass (shown in green above), and measurement marker (shown in red above) are positioned. As a force is applied to the device, the mass and marker will compress the spring and a displacement will be measured.

4.1 Spring-mass system

The spring-mass system is really quite self-explanatory. It includes a spring and mass. The system works as a force is applied to allow, yet control displacement (Figure 3). A force will cause the mass to displace, while at the same time the spring will control and limit the displacement.

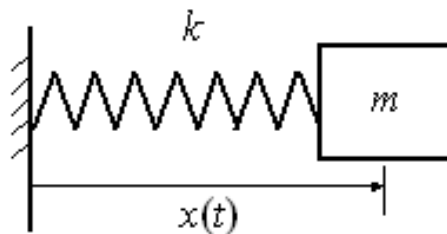


Figure 3. Spring-mass-damper system [3]

As the system is undergoing the various effects of the forces at work, one governing differential equation is very useful in understanding and predicting the behavior of the system. This differential equation (1) describes all of the

forces at work in the system, and serves to predict the behavior of the system. [4] Once values are chosen for the mass and spring rate all that is needed are initial conditions in order to fully anticipate the performance of the system.

$$mx'' + kx = f(t) \tag{1}$$

The first term, mx'' , is equivalent to mass times acceleration or Newton's Law. This term is present to describe the movement of the mass. The second term, kx , is Hooke's Law, that is the spring rate multiplied by the displacement of the spring. This term enables understanding of the spring's behavior within the system. The $f(t)$ term is simply the force being applied to the system causing the movement of the mass.

4.1.1 spring

The spring in the design of the mechanical accelerometer is meant to limit displacement. A spring is an elastic element whose purpose is to store energy through elastic deflection, however in this design the spring is more accurately described as storing acceleration. [5] In order to best utilize the spring within the system full understanding of the properties of a spring are required. First of all, realize that elastic elements have many equations and properties that govern their behavior. The spring being used in the mechanical accelerometer design is a compression spring, this somewhat limits the scope of properties that must be understood.

Primarily, spring rate is the most important area to be familiar with. From spring rate the dimensions of a spring are established, as are the forces required to produce a certain amount of displacement. (2) This concept is known as Hooke's Law, spring rate is equal to the force applied to the spring over the amount that the spring displaces in compression or extension from the applied force. (3) [6]

$$F = kx \tag{2}$$

$$k = f/x \tag{3}$$

A spring rate is chosen based on the range of forces that must be handled by the system. Three springs were found that seemed to have an adequate spring rate for the accelerometer. The springs were tested to discover their spring rates. It was found that two of the springs had rates nearly identical at 64 Newtons per meter (N/m). The third spring had a rate of 67 N/m. Although these differences seem very small, in testing it should be enough to establish any relationship based on varied spring rate.

4.1.2 mass

The mass used in the accelerometer design must be very precise in size. The final volume that the mass occupies in the accelerometer design is approximately one cubic centimeter. In order to utilize this small volume a dense mass was required. Two materials were used to create mass, lead and cero bismuth, two of each. These four masses were placed on a scale, and it was found that they ranged from 8.23 grams to 9.10 grams. In testing it was hoped that the four masses would serve to establish a relationship as to how mass affects the performance of the accelerometer.

5. Applications

There are many possible applications for a mechanical accelerometer. As previously mentioned, present accelerometer technologies are not adequate to use for certain applications. The new design of a mechanical accelerometer capable of saving the displacement could be used for any application requiring mobility and flexibility. Some of these possible applications could include use in sports equipment for injury analysis, or placement within vehicles for use in accident reconstruction. These applications would not be possible with present accelerometer technology, due to the dependence of present technologies. These applications would also best be served with a multi-axis accelerometer. A two or three axis accelerometer would allow for vectorial analysis to be performed. Vectorial analysis would aide in understanding the forces at work and how these forces were applied to the system being analyzed.

6. Testing & Calibration

Once the accelerometer design is completely assembled, it must first be calibrated before any usage is allowed. There are various tests used to calibrate existing electrical accelerometers. These tests primarily include varying-g pendulum testing and centrifuge testing. The varying-g pendulum test has limitations in that only accelerations of one g and below will be measured. The mechanical accelerometer design is intended to measure accelerations larger than one g, therefore this test may prove to be inadequate.

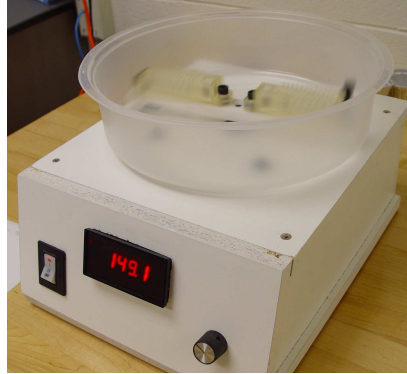


Figure 4. Centrifuge Test

The centrifuge test involves placing the accelerometer onto a platform that will rotate and utilize the centripetal acceleration in calibrating the accelerometer. An electrical tachometer (Figure 4) will read the revolutions per minute (RPM) and this will be translated into a frequency. A relationship between frequency and acceleration can be established in order to then create a relationship between the acceleration experienced by the accelerometer and the displacement created by that acceleration on the device. (4) The radius term was taken as an average at each location where the marker could stop.

$$a_c = 4\pi^2 r f^2 \quad (4)$$

Testing that was performed using the centrifuge used two of the three springs and all four masses. Each spring was tested in combination with each mass, a total of eight test runs.

7. Results

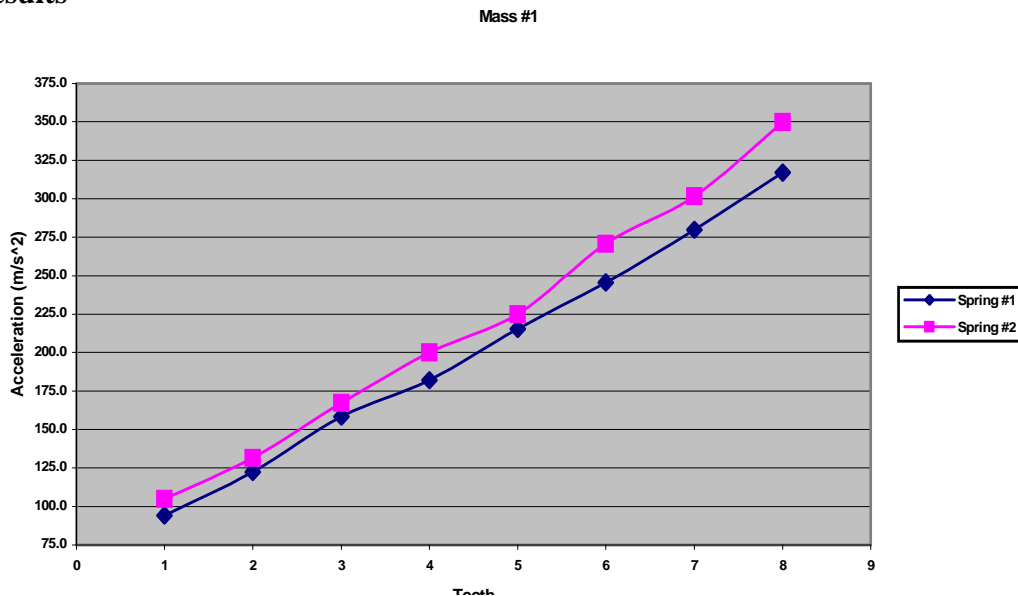


Figure 5. Graph of test data

The data shown in the above graph is from two tests. (Figure 5) One mass was used in both tests, but a different spring was used for each test. This graph very nicely demonstrates how varying the spring rate changes the performance of the system. Spring #1 from above has a rate of 64 N/m, less than that of spring #2.

The testing data that was taken from keeping the spring constant and varying the masses proved to exhibit no evident relationship. The masses all took fairly similar acceleration readings, as long as the spring remained constant.

8. Conclusion

The data resulting from the centrifuge testing proved a few things about the accelerometer design. One is that the device is capable of measuring quite a range of accelerations, from eight to thirty-eight g's (84.7 m/s^2 to 372.5 m/s^2) depending on the spring-mass combination being used. Although eight g's is slightly high, it is still practical, however thirty-eight g's is not very practical for use on earth. The key to adjusting the range of g's that will be read by the device lies in the spring rate. In order to lower the g's the device can read, the spring rate of the spring being used needs to be lowered. This alone should enable the device to take readings of lower accelerations making applications of the device more practical. Implementing a spring with a lower rate is also a very simple task.

Another thing that the testing proved is that the device measures only the peak acceleration experienced by the device. (Figure 6) No compound acceleration readings were taken during testing. This was a problem anticipated early on in the design process. Use of the spring was intended to prevent compound acceleration readings.

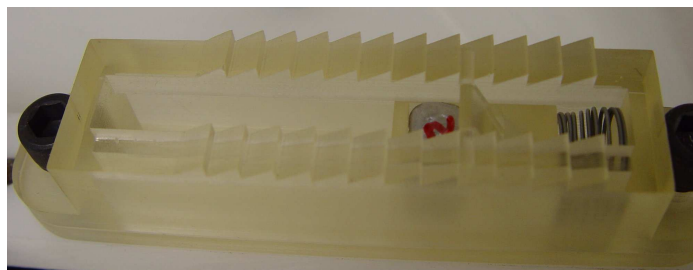


Figure 6. Displaced mass in accelerometer

Once a self-contained mechanical accelerometer is fully developed, possible applications will be broadened due to the independence and recording features of this new design. Eventual expansion into a three axis device will also further increase the applications of an accelerometer.

9. Acknowledgements

The author would like to thank the National Science Foundation (NSF) and the Milwaukee School Of Engineering (MSOE) for funding the Research Experience for Undergraduates (REU) that made this research possible. Appreciation is extended to the staff of the Rapid Prototyping Center. Special thanks also to Dr. Larry Fennigkoh for devising this project and serving as a wonderful advisor, Ann Bloor and Betty Albrecht for their kindness and guidance, and the other eight REU participants. A most humble thanks is also extended to Guy and Carol Krugjohn, the author's parents, for their consistent support and love throughout the years.

This material is based upon work supported by the National Science Foundation under Grant No. EEC-0139142. Any opinions findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Science Foundation.

10. References

- (1) Edgar, Julian. "Performance Testing, How to test your performance mods on the road" Autospeed [online]
http://www.autospeed.co.nz/A_0243/cms/article.html

- (2) <http://www.msoc.edu/rpc/sla.shtml>
- (3) http://www.efunda.com/math/laplace_transform/example.cfm
- (4) Zill, Dennis G. A First Course in Differential Equations. 5th Ed. Brooks/Cole, 2001.
- (5) Relvas, Abilio A. "Springs." Associated Springs, Barnes Group. Rpt. in Mechanical Design and Systems Handbook. Ed. Harold A. Rothbart. 2nd Ed. New York: McGraw-Hill, 1985.
- (6) Andreeva, L.E. Elastic Elements of Instruments. Ed. V.I. Feodos'ev. Trans. A. Baruch and D. Alster. Jerusalem: Israeli Program for Scientific Translations, 1966.