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EML 4905 Senior Design Project

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REQUIREMENT FOR THE DEGREE OF
BACHELOR OF SCIENCE
IN
MECHANICAL ENGINEERING

SMA PASSIVE SHOCK ABSORBER
25% REPORT

TEAM VIBRANIUM

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This B.S. thesis is written in partial fulfillment of the requirements in EML 4905. The contents represent the opinion of the authors and not the Department of Mechanical and Materials Engineering.

ETHICS STATEMENT & SIGNATURES

The work submitted in this B.S. thesis is solely prepared by a team consisting of Harold Hastings and Alexander Zuleta and it is original. Excerpts from others' work have been clearly identified, their work acknowledged within the text and listed in the list of references. All of the engineering drawings, computer programs, formulations, design work, prototype development and testing reported in this document are also original and prepared by the same team of students.

Harold Hastings Team Leader	Alexander Zuleta Team Member

Dr. Norman Munroe
Faculty Advisor

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Abstract

A prototype of passive-damping shock absorber intended for the Florida International University (FIU), Formula Society of Automotive Engineers (SAE). This shock absorber was motivated by the idea of an adjustable long-life shock absorber with limited to no moving parts and/or working fluid. Due to the simplicity of the mechanism, with respect to its moving components, it was anticipated that a highly reliable weight optimized prototype could be realized for Formula SAE. Additional considerations for use earthquake damping systems were discussed, but due to time constraints it was not pursued.

Due to the exotic material properties as well as compatibility considerations with existing hardware this project was divided into the following four phases: Phase I: Material Selection, Phase II: Design, Phase III: Analysis and Phase IV: Manufacture. In Phase I a rough estimate of the working load was established and specific material properties of current automotive springs were analyzed (i.e. Young's modulus and yield strength of SAE 9254) and based on the resultant data an alloy of Nitinol™ (binary or ternary alloy has yet to be determined at this time) was chosen that had similar properties. During Phase II the geometry of a standard MacPherson Strut was analyzed and an initial concept for a design that would be compatible with existing automotive was explored. After the problem was well defined and constrained several rough sketches were conceived. Subsequently an appropriate design of the spring which was to be the focus of the shock absorber will be decided upon. SolidWorks® will be utilized as the primary design software package. At Phase III analysis of the Nitinol™ springs was performed as well as the shock absorber as a system to ensure that proper standards and proof of concept was achieved. ANSYS and SolidWorks® will be the primary software packages used in Phase III.

As the foundation was laid by the previous phases Phase IV cannot be adequately described at this time.

Introduction

Problem Statement

The purpose of this senior project was to design and fabricate a prototype of an automotive suspension system which would reduce weight, offer a longer useful life, as well as provide the necessary adjustability that conventional racing-style dampers provide.

Motivation

The design project was motivated by Alexander Zuleta's previous experience working with Nitinol™ and his desire to continue using this exotic material. Harold Hastings suggested that the material's property would be well suited for damping vibrations. This initially prompted a discussion about an isolation table and that discussion eventually guided them to a fluid less passive damping shock absorber. Subsequently the question of "a need" was posited and determined that high-end racing car suspensions were in need of a highly reliable adjustable light-weight suspension system and could positively benefit from such a product.

Once the concept was visualized and a need was determined research on the material and concept to confirm the feasibility of the conceptual design was executed. Hence, Team Vibranium was established and following a consultation with their advisor, Dr. Norman Munroe, project planning and literature survey was initiated.

Literature Survey

History & Background Information

Nitinol™ is a popular metal alloy that belongs to the small group of the SMA class. Its crystalline configuration allows it behave in two ways: superplastic and "smart" in the sense that it can return to shape after being excessively deformed without experiencing plasticity. Its properties reside in the material response to heat or mechanical deformation which causes a variation in its Young's modulus and phase transformation.

It was discovered in the 1960's as part of a Naval Ordinance Lab project, and gained popularity for its high biocompatibility and the high recovery forces that can be generated when the material is properly constrained during phase transformation. Such interesting behavior drives research and enthusiasts to innovate into new applications every day.

Applications

Nitinol™ has been extensively used in medical applications due to its high biocompatibility, flexibility, and desirable surface finish which protected the material from environmental factors and made it practical for use in the human body; Stents are the typical type of medical devices that make use of the SMA's super elastic properties to expand clogged arteries or serve to support the vein walls.

Yet another application that has become popular is the fabrication of Ni-Ti Actuators that make use of the shape memory property by producing work when passing electric current through it which produces heat initiating the phase change which allows it to act as a switch or tendon.

Material & SMA Properties

Standard binary Ni-Ti Alloys are made out of Nickel and Titanium at approximately a 50%-50% concentration with slight variations. Ternary elements can be also added to extend the material properties and create new alloys that fit specific applications. Some examples of ternary alloys are: Ni-Ti-Co (Cobalt alloy), Ni-Ti-Cu (Copper Alloy), Ni-Ti-Fe (Iron Alloy), and others.

The internal atomic arrangement of Nitinol can be present in two phases as martensite and austenite. Both phases have different properties and the material can jump from one phase to another depending on the stress or temperature applied. The transformation temperature can vary in materials with different concentrations and compositions. By heat treating the SMA the transformation temperature can be altered and "re-trained" into a new shape. The addition of ternary elements to the material could change the temperature transformation in both directions.

When fully austenitic phase is present the material behaves as super elastic with a higher young modulus and with the ability to fully recover after excessive deformation. Super elastic alloys are also characterized for having low transformation temperatures and being already austenite at ambient conditions. On the other hand Shape memory alloys have a high transformation temperature and require extra power to initiate a phase change. Such characteristics make it useful for making actuators that can be turn on by just running current through the material.

Ni-Ti alloy's response to loading and temperature change is nonlinear and special simulation models should be used to predict the behavior. There are several Finite Elemental Analysis (FEA) software packages on the market that can simulate Nitinol™ including SolidWorks® which has an SMA model included in the customs materials section. By utilizing

FEA stress and fatigue analysis, one could aid in the development and optimization of innovative and reliable products.

The demand of Nitinol has increase globally along with the competition for better quality and price. The material has also been recognized by the FDA (Food and Drug Administration) as a safe material. Nitinol is sold in wire, sheet, rod, or billet form with a variety of diameters and sizes.

Project Formulation

Overview

The design of a Nitinol–based suspension was conceptualized as a way to use the material's damping properties and its strong response to heat to have a variable system that could outperformed in different situations. By constructing martensitic- Nitinol springs and controlling its phase transformation, the system response can be manipulated since the martensitic phase shows stronger damping ratios than austenitic.

Project Objectives

- To Prototype a variable damping ratio shock absorber with the use of Nitinol as active material
- To control the characteristics of the suspension by using an electrically controlled heating source.
- To effectively damp high amplitude inputs

Design Alternatives

Overview of Conceptual Designs Developed

As previously described, reference Motivation, the need and feasibility of a fluid less passive damping shock absorber was determined to be adequate in order to proceed with the conceptual design. With the intention of narrowing the scope of the project the following constraints were posited: Ni-Ti Shape Memory Alloy (SMA) that would allow the user to control the transformation temperature, spring design that will effectively use the tubular housing that will contain it, utilize existing hardware (shock absorber tubular housing and mounting points) for backwards compatibility and for reference geometry, multiple Ni-Ti alloy compression springs and mounting plate that will dissipate the energy stored in the coil spring, and a thermal delivery system that will regulate the temperature of the SMA which will allow the user to control the phase of the SMA.

Due to the standardized nature of shock absorber housing the subsequent design alternatives were focused on the design springs because the design problem is well defined and constrained.

Design Alternative 1

A Variable Pitch Cylindrical Spring (VPC Spring, See Figure 1) was the initial design that was chosen for the springs. This was due to the non-linear load vs. deflection curve that minimized resonant surging and vibration [9]. Because Ni-Ti alloys have a much smaller Young's Modulus than standard cylindrical springs are not suitable as the size and pitch of the spring necessary to dampen vibrations through a vehicle would be cost prohibitive and too bulky for the housing. It should be possible through careful calculations, to design a spring such that the work generated by the spring would be greater than or equal to the work done the on vehicle through vibrations.

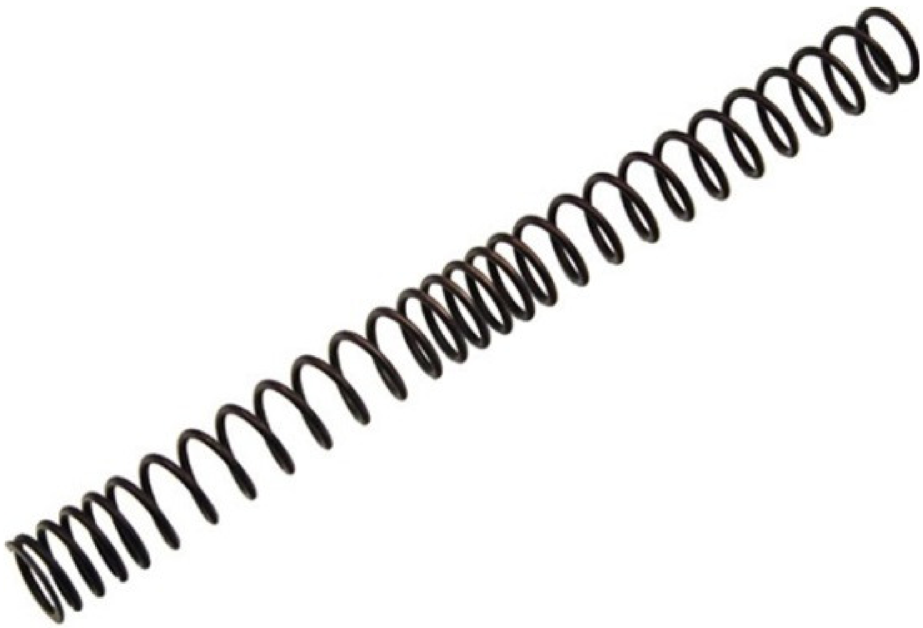

Figure 1 VPC Spring [5]

Design Alternative 2

A Flat Spring (See Figure 2) was the next obvious alternative for the reason that this particular variation of the spring provides more travel for the spring which is ideal for a design with limited space. The difficulty with this design is reducing the buckling of the spring in such a relatively large volume. There is also a concern of if a spring of suitable strength could be produced with the combination of this type of spring and material.

Figure 2 Flat Spring [4]

Other Considerations

Due to the nature of the project, the utmost importance and meticulous deliberation must be afforded to the alloys under consideration. The binary Ni-Ti alloy was the primary consideration for the springs, but there was some concern that these alloys would not be stiff enough in the Martensitic phase which is the phase that performs most of the damping by converting potential energy into strain and ultimately heat. This also suggested that the temperature of the alloy would need to be regulated in order to control the phase distribution within the alloy. The real possibility of a binary Ni-Ti alloy that was not sufficiently strong has guided Team Vibranium to explore the ternary alloys. A Ni-Ti-Co composition has shown initial promise, but the control of the phase transformation appears to be below expected operating temperatures and therefore difficult to control.

The thermal delivery system has yet to be conceptualized as the spring design has yet to be determined. Team Vibranium will be considering conduction, advection, and convective delivery systems.

Feasibility Assessment

The feasibility of the aforementioned design alternatives initially appears fairly simple and achievable. However, upon further inspection into the problem it is clear that the material must first be selected in order to properly choose the correct spring. By this logic and by comparing currently/historically used automotive spring materials and comparing the Modulus of Resilience, it is immediately apparent that binary Ni-Ti would be suitable. In the interest of thoroughness, vendors that produce the ternary alloys have been contacted and Team Vibranium is currently awaiting the properties of the various alloys to complete the material analysis (See Table 1). Assuming that binary Ni-Ti alloy is a suitable material there are already Ni-Ti springs available on the market, which suggests that the manufacturability is only a matter of price.

Table 1 Material Selection Analysis

Alloy	Modulus of Elasticity (N/m^2)	Shear Modulus (N/m^2)	Yield Strength (N/m^2)	Modulus of Reslience (N/m^2)	Range of Er +/-10%
SAE9254	2.000E+11	7.800E+10	1.034E+09	2.673E+06	2.406E+06
SAE9260	2.000E+11	8.000E+10	1.149E+09	3.301E+06	1.058E+07
Ti-6Al-4V	1.200E+11	4.500E+10	8.850E+08	3.263E+06	
Ti-10Fe-2Mo-3Al	1.070E+11	4.210E+10	1.200E+09	6.729E+06	
Ti-4.5Fe-6.8Mo-1.5Al	1.170E+11	4.300E+10	1.500E+09	9.615E+06	
Ni-Ti (Martensitic)	4.100E+10	2.880E+10	5.600E+08	3.824E+06	
Ni-Ti-Ta	3.700E+10				
Ni-Ti-Nb					
Ni-Ti-Co					
Ni-Ti-Mo					

Proposed Designs

Design 1

Based on the constraints of the standard shock absorber, the shock damping apparatus must fit within the standard housing (See Figure 3). Using this as a geometric parameter there would be a total of 8 Ni-Ti springs will be attached to the spring housing (See Figure 4).

The spring housing will be free to slide within the lower blue (See Figure 3) tube and will be constrained by the lower guide rods which will also prevent buckling of the lower springs (See Figure 6). The lower guide rods will be concentric and fit within the hollow inner diameter of the upper guide rods. The eight springs, four on each side attached at the nipples, will be fixed to the interior of the extreme ends of the shock absorber housing. The assembly (See Figure 5 and Figure 6) is anticipated to appear and operate as a standard shock absorber.

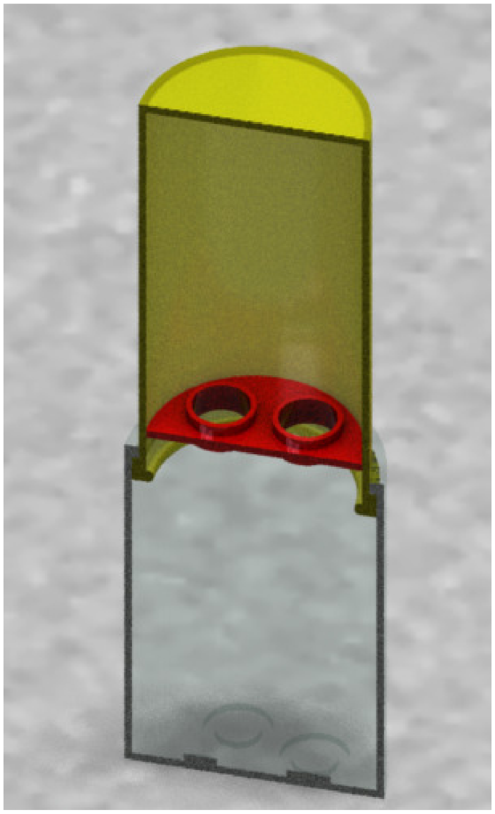

Figure 3 Shock Absorber Housing

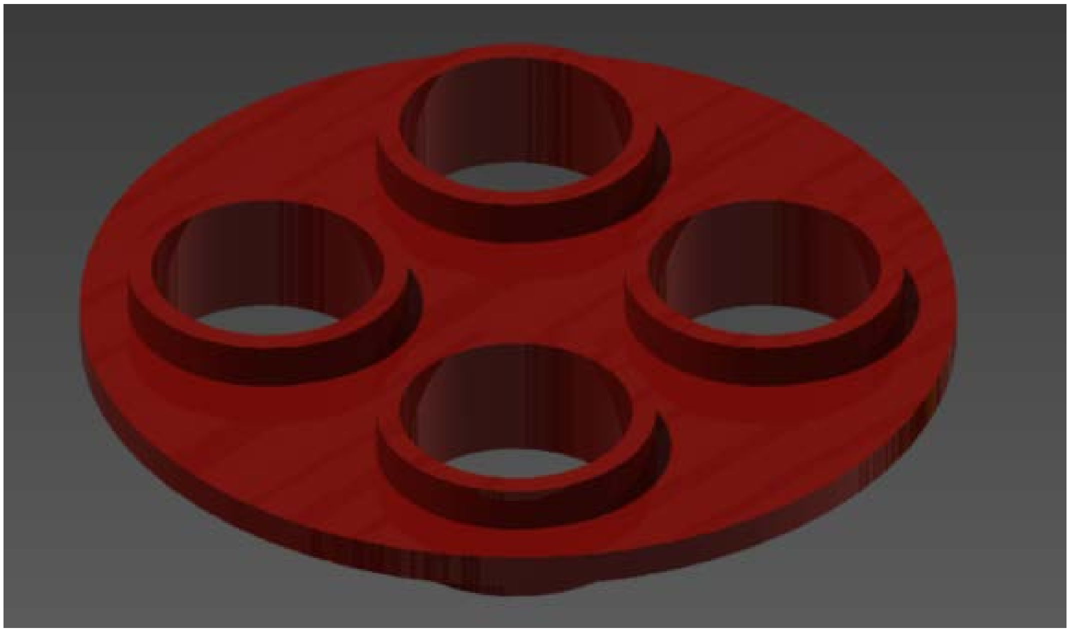

Figure 4 Spring Housing

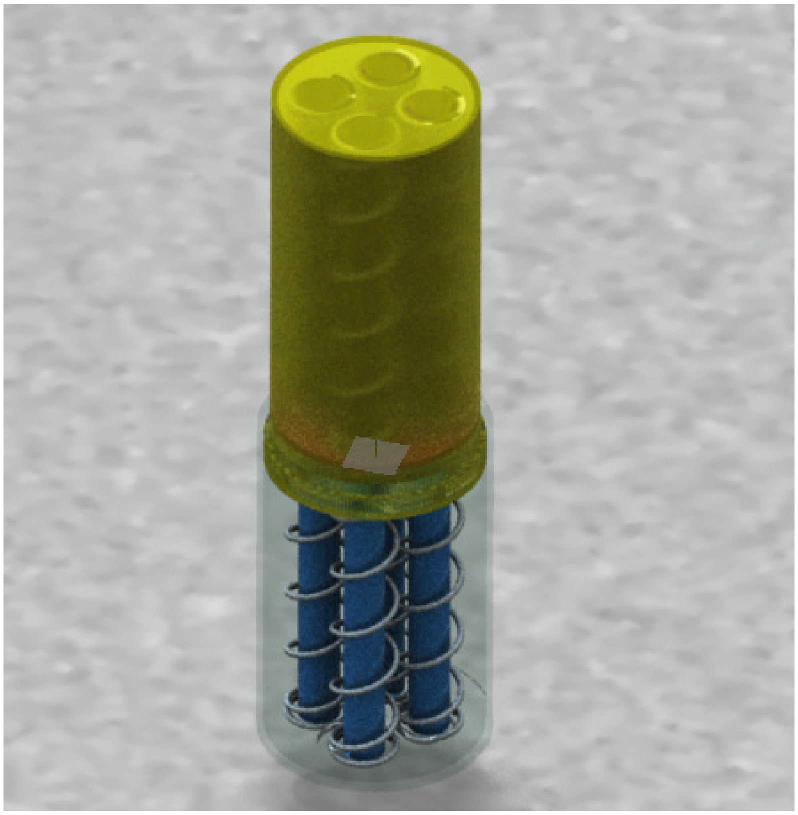

Figure 5 Ni-Ti Shock Absorber Assembly

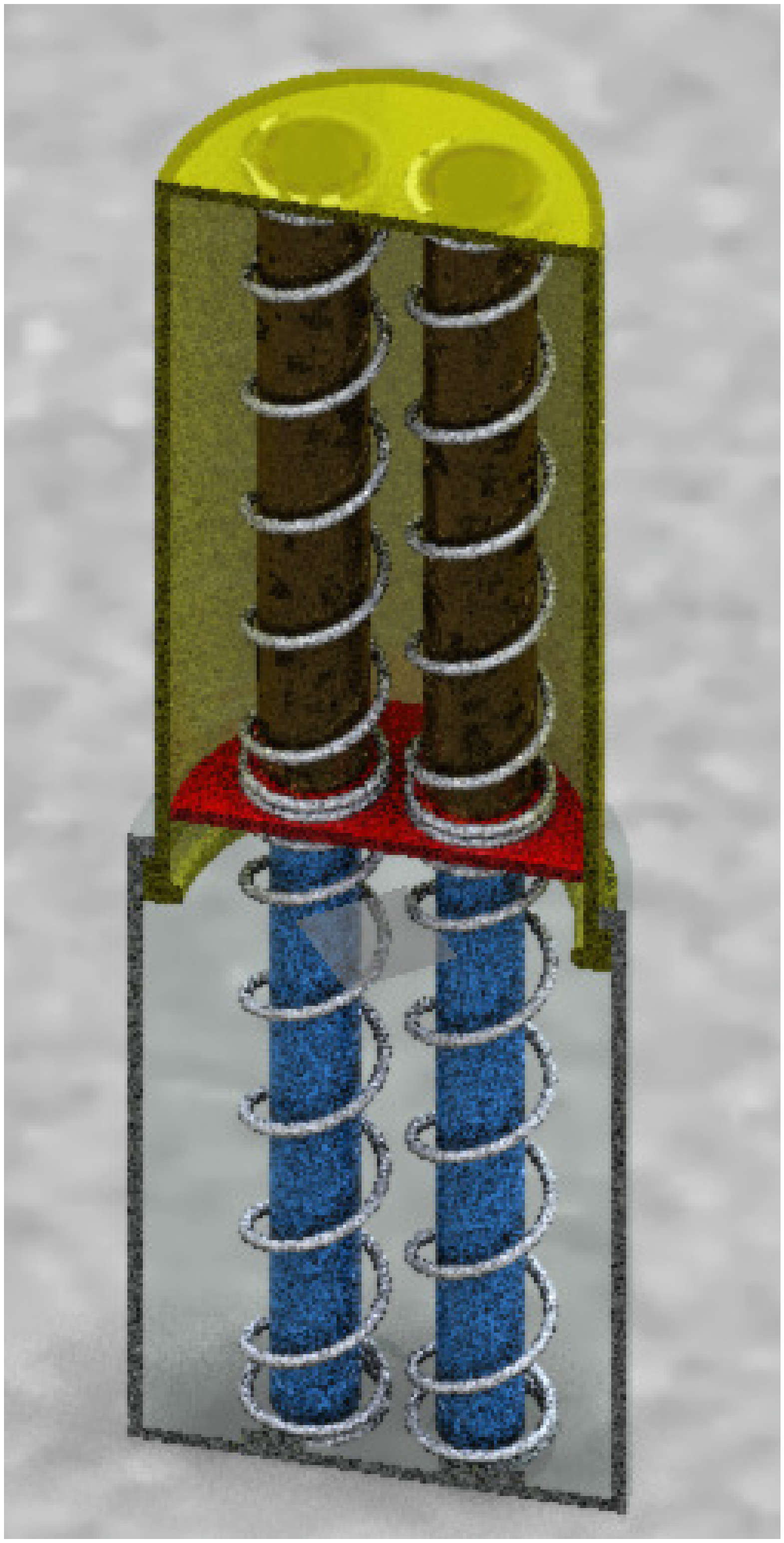

Figure 6 Ni-Ti Shock Absorber Assembly Section View

Design 2

This design was conceptualized thinking about how to maximize the damping ratio in both directions. The assembly uses 8 shape memory alloy springs (See Figure 7).The black plate is free to slide and able compress the top and bottom springs. The springs are fixed to the black plate and the frame. The red ends are tightened with screws to the shafts.

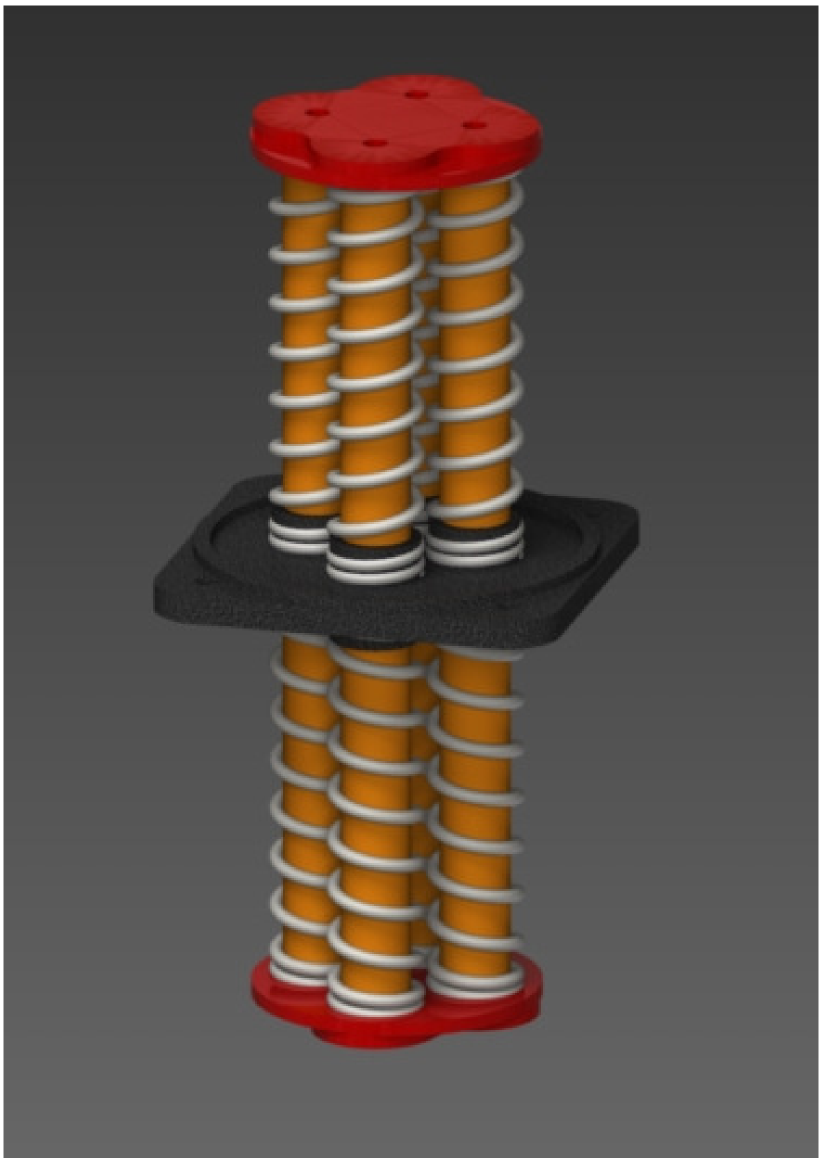

Figure 7 SMA Shock Absorber Concept

Project Management

Overview

Drawing on each other's experience and strengths the breakdown of work into specific tasks (See Table 2) was devised. Despite being limited to only two people tasks were assigned uniformly based on estimated time to complete and intensity of labor.

Division of Labor

Table 2 Division of Labor

	Project Formulation	Design Alternatives	Proposed Design	SolidWorks Analysis	ANSYS Analysis	Part List/Cost Analysis	Prototype Construction	Prototype Testing	Prototype Organization	Report Preparation
Harold Hastings										
Alexander Zuleta										

Organization of Work & Timeline

Table 3 Project Timeline

	Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
Project Formulation																						
Design Alternatives																						
Proposed Design																						
SolidWorks Modeling																						
SolidWorks Analysis																						
ANSYS Analysis																						
Part List/Cost Analysis																						
Prototype Construction																						
Prototype Testing																						
Team Poster																						
Protoype Organization																						
Report Preparation																						
Final Presentation																						

Engineering Design & Analyses

Overview

In order to analyze and predict the behavior of Nitinol springs a FEA analysis was proposed as a starting point. The Solidworks^{TM} CAD package already includes a non-linear model for simulating Nitinol shape memory alloys and which can be calibrated to the specific alloy in use. The results are then compared to some theoretical data which has been prepared using a tabulated spring formula spreadsheets in order to identify the maximum and minimum spring rates and deflection for given temperature and forces.

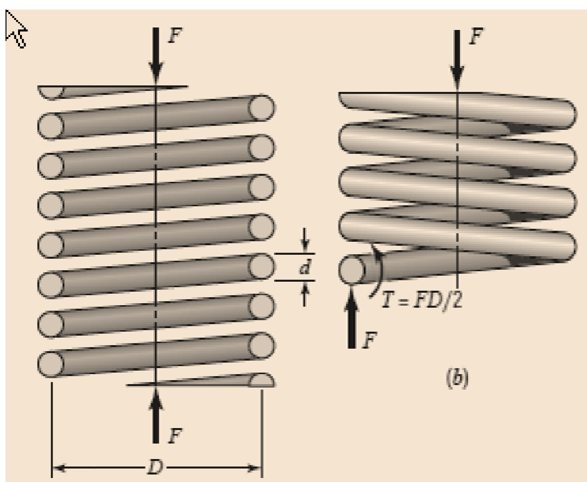

Figure 8 Spring Force Diagram

Structural Design

It was proposed that the shock absorber should contain all the moving parts enclosed by two relative moving shells (figure 9) which resembles that of a standard damper. In the interior the red plate moves relative to the yellow guide rods while the blue guide rods slide inside of the yellow guide rods. Additionally, 8 springs are used in both sides to capture motion in all direction; the springs should be crimped or fixed to the red plate and end walls.

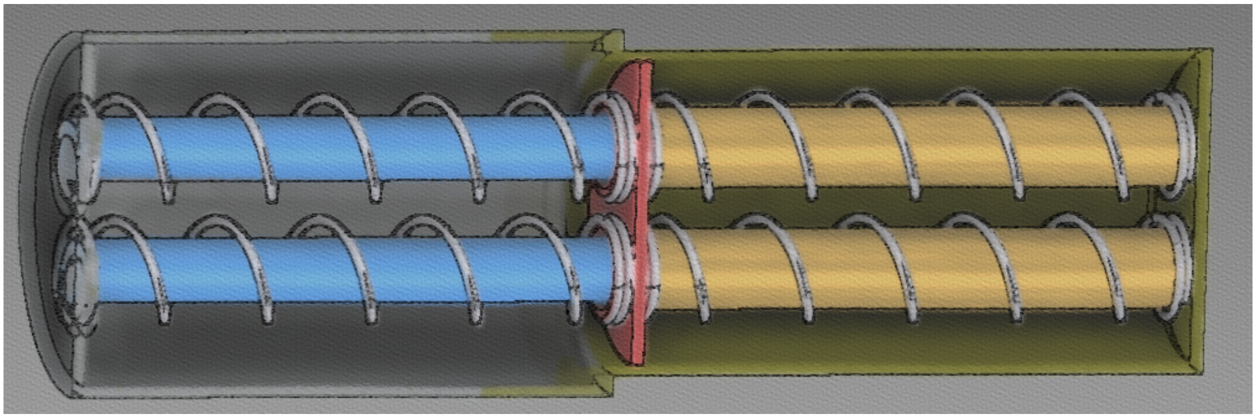

Figure 9 Shock Absorber Assembly Section View

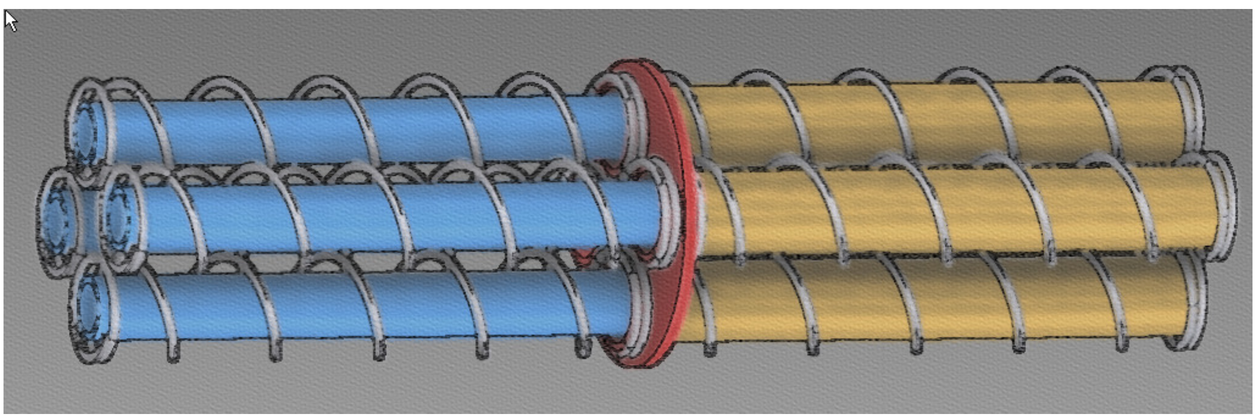

Figure 10 Internal Spring Configuration

To select the appropriate dimension of the spring dimension a tabulated table was prepared by using the following material formula to determine the spring constant:

$$k \doteq \frac{d^4 G}{8 D^3 N}$$

The shear modulus will be a function of temperature since the young modulus varies throughout the phase transformation from martensitic to austenitic and which range is between 40 and 70 GPa for standard binary alloys.

Table 4 Spring Constant with Varying Wire Diameter and Fixed Spring Diameter

Youngs Modulus	40000000000		INPUTS
Poisson's ratio	0.3		OUTPUTs
Shear Modulus	28571428571		
Number of coils	6		
Spring diameter	20		

Wire Dimater (mm)	Spring Diameter (mm)	Spring rate (N/mm)	lb/in
1	20	0.0744	0.4249
2	20	1.1905	6.7978
3	20	6.0268	34.4138
4	20	19.0476	108.7646
5	20	46.5030	265.5385
6	20	96.4286	550.6206
7	20	178.6458	1020.0927
8	20	304.7619	1740.2331
9	20	488.1696	2787.5170
10	20	744.0476	4248.6161
11	20	1089.3601	6220.3988
12	20	1542.8571	8809.9303
13	20	2125.0744	12134.4724
14	20	2858.3333	16321.4835
15	20	3766.7411	21508.6189

The total sliding travel of the system is determined by the geometry constraints of the spring which embraces solid height, free length and spring diameter as shown in the following tables in which some parameters vary and other held fixed.

Table 5 Variable Pitch and Fixed Wire Diameter and Number of Coils

SPRING DESIGN	Helical Compression Plain				
Given (p) and (d) and (Na)	(mm)				
Pitch(p)	20				
Wire diameter (d)	4				
Number of coils (Na)	6				
Pitch(p)	**Wire diameter (d)**	**Coils (Na)**	**Free Length (L0)**	**Solid Length (Ls)**	**Travel**
1	4	6	10	28	-18
2	4	6	16	28	-12
3	4	6	22	28	-6
4	4	6	28	28	0
5	4	6	34	28	6
6	4	6	40	28	12
7	4	6	46	28	18
8	4	6	52	28	24
9	4	6	58	28	30
10	4	6	64	28	36

Table 6 Variable Number of Coils and Fixed Wire Diameter and Pitch

Pitch(p)	Wire diameter (d)	Coils (Na)	Free Length (L0)	Solid Length (Ls)	Travel
20	4	5	104	24	80
20	4	6	124	28	96
20	4	7	144	32	112
20	4	8	164	36	128
20	4	9	184	40	144
20	4	10	204	44	160
20	4	11	224	48	176
20	4	12	244	52	192
20	4	13	264	56	208
20	4	14	284	60	224

Table 7 Variable Wire Diameter and Fixed Pitch and Number of Coils

Pitch(p)	Wire diameter (d)	Coils (Na)	Free Length (L0)	Solid Length (Ls)	Travel
20	1	6	121	7	114
20	2	6	122	14	108
20	3	6	123	21	102
20	4	6	124	28	96
20	5	6	125	35	90
20	6	6	126	42	84
20	7	6	127	49	78
20	8	6	128	56	72
20	9	6	129	63	66
20	10	6	130	70	60

Stress Analysis & Finite Elemental Analysis

Nitinol is a material that experiences very large strains compared to other metals and in order to simulate such material properties, a specialized FEA non-linear algorithm must be applied. The Solidworks^{TM} simulation package powered by D'assault Systemes includes a SMA Nitinol Material model that is of easy configuration and which also provides results for stress concentration and cyclic loading test. The following figures show a simulation performed over a 4mm wire diameter spring using the SMA model.

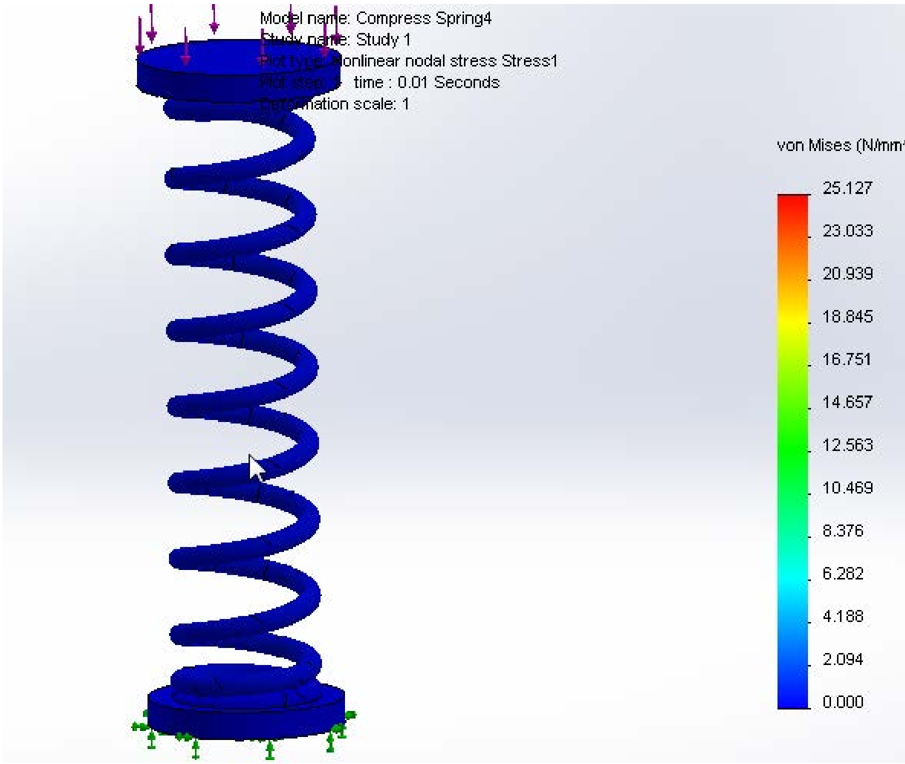

Figure 11 Unloaded Nitinol Spring

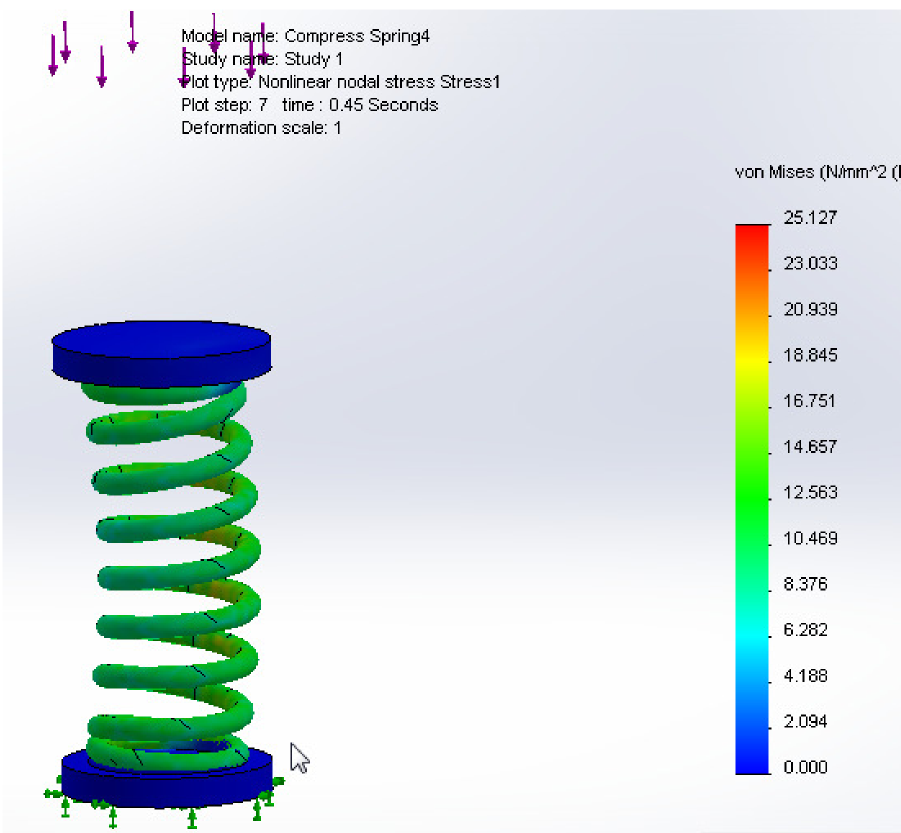

Figure 12 Loaded Nitinol Spring

Design Overview

Cost Analysis

Table 8 Cost Analysis Table

Item	Quantity	Expected Cost	Actual Cost	Expected Maching Cost	Actual Machining Cost	Material	Vendor
Spring	8	$128.40	$0.00	$0.00	$0.00	Ni-Ti	NDC
Upper Housing	1	$29.28	$0.00	$50.00	$0.00	6061 T6	OnlineMetals.com
Lower Housing	1	$16.52	$0.00	$100.00	$0.00	6061 T6	OnlineMetals.com
Spring Plate	1	$46.32	$0.00	$250.00	$0.00	6061 T6	OnlineMetals.com
Upper Endcap	1	$0.00	$0.00	$75.00	$0.00	6061 T6	OnlineMetals.com
Lower Endcap	1	$0.00	$0.00	$75.00	$0.00	6061 T6	OnlineMetals.com
Subtotal	1	$220.52	$0.00	$550.00	$0.00		
Estimated Total Cost	$770.52						
Actual Total Cost	$0.00						

The cost analysis that has been provided (See Figure 13) has been based off of costs provided by the vendors, and an estimate of machining time based on complexity of parts at a rate of $50.00 per hour. At this juncture of the design the cost analysis is only a Bill of Materials (BOM) with associated costs. However, once the thermal delivery system has been designed and optimized a more accurate cost analysis can be generated. The primary reason for this is the thermal delivery system is the only subsystem that requires power and has electrical components which may fail.

Additionally, the components Lower End cap and Upper End cap have not been previously referenced because as the proposed design was refined Team Vibranium discovered that no consideration was lent to assembly of the system and minimizing the cost of the system. During this epiphany, it was evident that the design proposal required modification to reduce manufacturing costs and these modifications will be evident in the next revision.

Testing & Evaluation

Overview

Insofar as the testing of the system, Team Vibranium currently plans to manufacture a specialized testing rig that can inject a controlled frequency of varying force and amplitude into the system. The response of the system will then be measured. The data collected will be analyzed and a transfer function will be created and a ratio of the input/output frequencies and amplitudes will be generated which will determine the effectiveness of the system.

Design of Experiment

This will be accomplished by a cam or linear actuator that will impart a pre-determined impulse at a predetermined frequency. The dynamic response of the system will be measured by a Digital Laser Doppler Vibrometer (DLDV), the temperature will be monitored by thermocouples, and a power source for the thermal delivery system.

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