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Anna Tombazzi
ast23@zips.uakron.edu

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Design of Shape-Conforming Nosecone for Optimal Fluid Flow from Transonic to Supersonic Range

Senior Honors/Design Project 4200:497

Anna Tombazzi

Faculty Advisor: Dr. Jiahua Zhu

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Executive Summary

Background

Modern flight vehicles, such as rockets, missiles, and airplanes, experience a force caused by forebody wave drag during flight. This drag force is induced on the vehicle body when the frontal point of the vehicle breaks the air pressure wave during flight. Efforts to reduce this wave drag force in order to improve flight efficiency include modifying the nosecone profiles of flight vehicles.

Different nosecone profiles are optimal for reducing drag at different velocities and start to make a notable difference above Mach 1. Unfortunately, a flight vehicle can only sport one nosecone during its entire flight, even though it experiences a range of velocities. Therefore, no matter what nosecone is selected for the vehicle, there is always a tradeoff in performance because the nosecone which has an optimal drag characteristic for one velocity is sub-par at another velocity. This project revolved around creating a design to make the transformation between two nosecone shapes possible midflight, in order to avoid efficiency tradeoffs associated with just using one nosecone geometry.

Results

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Conclusion

A design was created to make the transformation of nosecone shapes from a \(\frac{3}{4}\) Parabolic profile to a \(\frac{1}{2}\) Power Series profile possible, mid-flight. Using a novel nosecone assembly, shape memory alloys (SMAs) and an electronics system, this transition will be dictated by a vehicle’s real-time flight velocity. Electronics sense the change in velocities and activate the transformation through a release of current once the rocket reaches Mach 1.2.

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Technical, Career, and Personal Implications

This technology could benefit society through its use in aerospace applications to improve flight efficiency. On a more personal level, it could improve the possibility of opening up supersonic flight to the public once again. For example, Boom Supersonic is currently designing planes which they hope the public will one day use as a mode of transportation. However, there are many design challenges as one might imagine- including cutting down the drag resistance experienced by the plane inflight, which translates to having to carry more fuel.

This project was created in an effort to provide a shape-changing nosecone for use on the Akronauts Rocket Design Team, at the University of Akron. At one of the competitions the team competes in, rockets are launched as high as 30,000 ft. When rockets are designed to reach this altitude, they most likely will break Mach 1 and closely approach Mach 2, calling for a device like this nosecone which can change shape for each velocity milestone.
This project was inspired not only by the rocket team at the University of Akron, but also by a 2-minute briefing of shape memory alloys given during a material science lecture. Since the start of this project, I have learning an incredible amount about the chemistry and material science behind shape memory alloys. I have also had the opportunity to learn about electrical systems, and learn softwares like Matlab and Solidworks, which were required in order to bring this design to life.

Recommendations

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Introduction

For a rocket in flight, there are many forces that effect both the flight profile and fuel efficiency. One of these forces is the drag force experienced, which can be split into two components—wave-drag, and skin-friction drag. Drag in-flight for a rocket is undesirable mainly because it slows the rocket down, causing it to require more fuel to reach the same altitude. Rocket fuel is not only extremely costly but increasing the quantity of rocket fuel onboard also increases the total weight of the rocket, affects stability, and alters other factors in flight. Therefore, one of the primary goals when designing the exterior of a rocket is to minimize each parts’ drag coefficient, which corresponds directly to the magnitude of the drag force that will be imposed on that part.

The wave-drag, which is caused by the pressure forces on the rocket normal to the surface, is present on the nosecone, fins, and the after-body. Forebody wave-drag is induced by the nosecone, and as such, nosecones are designed in order to bring down the drag force on the rocket during flight. The magnitude of nosecone wave-drag is dictated by not only its shape, but also by the rocket’s velocity, and fineness ratio, which is the ratio of a nosecone’s length to its’ largest diameter (1). Fineness ratio is usually limited by the rocket’s total weight requirements, as the rocket’s velocity is predetermined from the mission of the rocket’s flight. There are many characteristic nosecone shapes which a modern rocket nosecone may be modeled after, namely the Tangent Series, Power Series, Parabolic Series, Haack Series, and the Von Karman (2). These nosecones are identified by their individual characteristic equation, which describes the curvature that the nosecone follows.

As rockets travel through the transonic region, which begins at Mach 0.8, and approach the speed of sound, Mach 1, the wave-drag that the rocket experiences sharply increases. Since wave-drag is a function of a rocket’s Mach number, each nosecone shape has different drag properties at different velocities. The preferred nosecone shapes corresponding to the Mach number is illustrated in Figure 1 (2). As seen, one shape may be preferred over the others at a certain Mach number, but will not be optimal over the total velocity range of the flight. Because there is a drag trade-off during flight with any nosecone choice, it is traditional to choose a nosecone shape which will have an optimal drag characteristic for the velocity that will be experienced the most frequently during the flight.
However, rockets soar through a wide variety of velocities during flight, from subsonic, to transonic, to supersonic, often not staying at the same Mach number for an extended period of time. Even if a nosecone is selected for optimal drag resistance at supersonic speed, drag tradeoffs will occur at other velocities. Furthermore, if a rocket is relaunched later for a different mission, where is now experiences a different flight velocity profile, the previously used nosecone may not be optimal over any of the velocities that the rocket will now fly at. At this point, either a new nosecone must be manufactured, or the rocket unnecessarily suffers from increased forebody wave-drag.

The basis of this project was to design a nosecone which could shape transform in between two different nosecone shapes, mid-flight, so that the rocket experiences a minimum wave-drag force throughout its’ entire flight. A sounding rocket designed by the Akronauts Rocket Design Team, which is expected to reach speeds of 1.9 Mach, was the target body for which this shape-conforming nosecone was designed for. Two nosecone profiles were chosen for which the nosecone will transform between. From Figure 1., it is seen that the Von Karman shape performs well from the transonic region until about 1.2 Mach. After that, from 1.2 Mach through 1.8 Mach, the $\frac{1}{2}$ Power Series design becomes preferable, experiencing less wave-drag from the fluid flow of air. The governing equations for the curvature of each nosecone shape are as follows, where $L$ is the total length of the nosecone, $R$ is the final radius, and $y$ is the instantaneous changing diameter of the nosecone along $x$, the varying distance from nosecone tip, as seen in Figure 2 (2).
Von Karman

\[ \Theta = \arccos \left( 1 - \frac{2x}{L} \right) \]  

\[ y = \frac{R}{\sqrt{\pi}} \cdot \sqrt{\Theta - \frac{\sin(2\Theta)}{2}} \]  

\[ y = R \cdot \left( \frac{x}{L} \right)^{0.5} \]  

Background

In order to accomplish this change between nosecone shapes mid-flight, the use of a shape memory alloy was employed. Shape memory alloys (SMAs) are metals which have the ability to transform between two different shapes. In metals, there exists different solid-state phases. Austenite is the phase that the metal transitions to at high temperatures, and martensite is the low temperature phase. The transition temperature range is referred to as the temperature range where the metal starts transitioning from one phase to another. \( A_s \) denotes the starting temperature where the alloy starts to change its’ phase from martensite to austenite, whereas \( A_f \) denotes the ending temperature where the alloy should be in its austenite phase completely. Likewise, \( M_s \) and \( M_f \) refer to the starting and ending temperatures through which the SMA is transforming into its martensite phase. As seen in Figure 3., there is often a temperature gap between the \( A_s \) and \( M_f \) temperature, which is called its hysteretic loss. The temperature transition ranges, such as \( A_s \) and \( A_f \), differ for different shape memory alloys, as the different alloy compositions dictate the temperatures at which the metal will be in its martensite or austenite phase. Common metals used for composing shape memory alloys include copper, nitinol, aluminum, iron, gold, and titanium.
To understand the significance of phase change on the effect of SMA shape, one must have a basic understanding of thermodynamics and its effect on the atomic structure of a material.

In order to lower Gibbs Free Energy, there exists an optimal arrangement of atoms within the SMA at each phase. In the austenite phase, the atoms assume a cubic crystalline structure, but in the martensite phase, the atoms reorient themselves to form either a tetragonal or monoclinic crystalline arrangement (4).

When a SMA cools from austenite to martensite without being under stress, twinned martensite is formed, meaning that the macroscopic shape of the material stays the same because its’ atoms assume the tetragonal structure by a freely rearranging themselves. However, if the SMA is cooled under a stress, then detwinned martensite is formed (5). The external stress does not allow the atoms to freely rearrange, and instead they shift to the tetragonal arrangement with respect to the load. For example, if the SMA is in tension stress during this phase change, this would cause a macroscopic extension of the material in the direction of the stress, as illustrated in Figure 4 (3).

![Figure 3. The SMA stress-temperature phase diagram, showing the typical progression in transition phase temperature ranges, as well as the hysteresis for this SMA.](image)

![Figure 4. Illustrates the atomic structure difference between detwinned and twinned martensite phase formation](image)

Thermomechanical processing, called training, is the process during which a SMA is repeatedly heated to its austenite phase and cooled to its martensite phase while under stress. After a number of cycles, it will automatically revert to its detwinned martensite structure after cooling, even after the stress is removed (7). Similarly, when the SMA is heated through its austenite transition range, its atoms will reform their cubic structure, no matter what shape the SMA has been contorted to in its martensite phase. The memory of the alloy where its low temperature detwinned martensite structure is retained after the its transformation from austenite to martensite without stress is called a two-way shape memory effect. In the case of detwinned martensite formed under tension stress, when the SMA forms its corresponding austenite phase, the material will contract macroscopically, caused by the microscopic contract of atoms back...
into their cubic structure (6). A visual of this is seen in **Figure 5**. In **Figure 6**, the characteristic behavior of a SMA change in strain with temperature and applied stress is seen.

![Figure 5. Atomic structure differences between detwinned martensite, twinned martensite, and austenite.](image1)

![Figure 6. Under stress, detwinned martensite is formed during cooling. Upon stress removal, the detwinned martensite structure remains until the material is heated to form its austenite phase.](image2)

Besides differing transition temperature ranges, different SMAs have unique characteristics corresponding to strain, corrosion, fracture properties, along with the number of cycles from austenite to martensite a SMA will be able to exhibit its one-way or two-way memory before breakdown. The benefits of Ni-Ti alloys with respect to its counterparts are seen by a comparison of its properties with other alloys, as seen in **Figure 7** (7).

<table>
<thead>
<tr>
<th>Property</th>
<th>Ni–Ti</th>
<th>Cu–Zn–Al</th>
<th>Cu–Al–Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting point (°C)</td>
<td>1250</td>
<td>1020</td>
<td>1050</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>6.45</td>
<td>7.9</td>
<td>7.15</td>
</tr>
<tr>
<td>Thermal expansion coefficient (10⁻⁹/K)</td>
<td>6.6–10</td>
<td>17</td>
<td>17</td>
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<tr>
<td>E-modulus (GPa)</td>
<td>95</td>
<td>70–100</td>
<td>80–100</td>
</tr>
<tr>
<td>UTS, martensite (MPa)</td>
<td>800–1000</td>
<td>800–900</td>
<td>1000</td>
</tr>
<tr>
<td>Elongation to fracture, martensite (%)</td>
<td>30–50</td>
<td>15</td>
<td>8–10</td>
</tr>
<tr>
<td>Fatigue strength at 10⁶ cycles (MPa)</td>
<td>350</td>
<td>270</td>
<td></td>
</tr>
<tr>
<td>Transformation temperature range (°C)</td>
<td>−100 to +110</td>
<td>−200 to +110</td>
<td>−150 to +200</td>
</tr>
<tr>
<td>Maximum one-way memory strain (%)</td>
<td>7</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Normal two-way memory strain (%)</td>
<td>3.2</td>
<td>0.8</td>
<td>1</td>
</tr>
<tr>
<td>Normal working stress (MPa)</td>
<td>100–130</td>
<td>40</td>
<td>70</td>
</tr>
<tr>
<td>Normal number of thermal cycles</td>
<td>+100,000</td>
<td>+10,000</td>
<td>+5000</td>
</tr>
<tr>
<td>Maximum overheating temperature (°C)</td>
<td>400</td>
<td>150</td>
<td>300</td>
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<tr>
<td>Damping capacity (%)</td>
<td>20</td>
<td>85</td>
<td>20</td>
</tr>
<tr>
<td>Corrosion resistance</td>
<td>Excellent</td>
<td>Fair</td>
<td>Good</td>
</tr>
</tbody>
</table>

**Figure 7. Properties of several SMAs which are manufactured by Advanced Material Technologies Pte Ltd (7).**

The use of SMAs has become increasing popular in a variety of applications of the past few years, as they have been recognized for their ability to transform shape with just a temperature change. For example, in aerospace applications, this property been proven useful in the hydraulics in plane wings, some of which are now being replaced with SMA actuators, running off of the heat from the engines. Not only are SMAs incredibly energy dense, but they are also

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very reliable, as the shape change relies on thermodynamic laws, instead of mechanical components.

In addition to being used in aerospace applications, the use of SMA are also being explored in the fields of biomedical engineering, robotics, and automotive engineering.

In this application, the use of SMAs were chosen because of their ability assume a different shape even if they are against external stress. Mechanical mechanisms of contorting the nosecone would not only be unreliable, but also extremely space-consuming. At each contortion point, there would need to be an individual mechanism to move the nosecone, since each point of the nosecone would have to be adjusted differently. However, a single current can be used to adjust the SMA wires, where they will all move simultaneously in different ways, to elicit the desired nosecone shape change.

**Design and Materials**

*Nosecone Shell Design*

In order to design the outside shell of the nosecone with the ability to undergo shape changes from the Von Karman to ½ Power Series nosecone, Matlab code was written to evaluate the step changes in radius for each nosecone shape. Starting at the tip of the nosecone geometry, denoted as length 0, incremental increases in length of the magnitude 0.1” were used to generate the corresponding radius of the nosecone shapes at each one of these lengths. An example of this data is displayed in Figure 8. The difference in radiiuses generated the distance the nosecone needed move in order to transform from Von Karman to a ½ Power Series shape.
As seen in Figure 8., there are relatively broad radius differences between each nosecone shape. Figures 9. and 10. show a CAD model of each individual nosecone shape in their typical, one-piece, solid fashion. After reviewing the data, it became clear that a single piece of material comprising the entire nosecone was not possible. A nosecone shell that could accommodate the excess material present after the transformation from the Von Karman to the ½ Power Series design was necessary.
Figure 9. A rendering of a Von Karman Nosecone. This rendering and drawing was made with AutoDesk Inventor and Solidworks.

Figure 10. A rendering of a ½ Power Series Nosecone. This rendering and drawing was made with AutoDesk Inventor and Solidworks.

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Experimental Procedures

Prototyping of Nosecone Shell

After constructing CAD models of the nosecone pieces, it was determined through analysis by multiple machinists that the best way to construct the geometry of the pieces would be through
3D printing. Before seeking out a metal 3D printing company to make this print, the possibility of printing out one piece of each geometry for prototyping at the University of Akron was explored. This was to ensure that the dimensions from the CAD drawings were correct and that the nosecone pieces would fit together correctly, before investing in an expensive aluminum 3D print. The mechanical engineering department did not have a plastic 3D printer large enough to print a nosecone piece 24” long, so it was decided that the nosecone pieces would be split up into different sections.

The nosecone pieces were sectioned into top, middle, and bottom sections. The middle sections were omitted from the print for the sake of time, but also because the middle sections were constrained by the top and bottom sections.

Therefore, if the top and bottom sections pieced together correctly, the middle sections must as well. One top section and one bottom section from each geometry was printed.

Training of SMA wires

In order to train the SMA wires supplied by Fort Wayne Metals, the expertise of NASA material scientist and SMA expert, Santo Padula, was employed. First, each wire was subjected to 200 MPa of constant stress. The weight in pounds, F, needed to induce 200 MPa of stress on each piece of wire, as a function of wire gauge g, was determined according to Equation 3. While under this stress, current supplied by a power source was ran through the wire, heating up the wire and inducing the solid-state phase change from martensite to austenite. Once the phase change had finished, characterized by heating the alloy past its $A_f$ temperature of the alloy, the current source was turned off and the wire was allowed to cool back to its martensite state. During cooling under stress, detwinning was experienced in the metal, as evident by its relaxation and resulting elongated martensite state. This heat cycling process was repeated until the strain in the metal changed no more than 1% from its previous strain in each phase.

$$F \text{ (lbf)} = (200 \text{ MPa}) \times 10^6 \times \frac{\pi \times (g)^2}{4} \times \left(\frac{25.4 \text{ mm}}{1 \text{ in}}\right)^2 \times \left(\frac{1 \text{ m}}{1000 \text{ mm}}\right)^2 \times \left(\frac{1 \text{ lbf}}{4.4 \text{ N}}\right)$$

(3)

The weights used to apply constant stress to the wires were steel weights created for the application of weight room workouts such as benching. These weights were used to induce stress on the material because the hole in the center of each of these weights created a convenient attachment point. A weight stand was created to support the weights during SMA training and was designed so that weights could be easily added or removed from the stand. As seen in Figure 17., the weight-stand consists of a large eyebolt, plywood, and a circulate 1/16” steel plate backing it. The 1/16”steel plate and ½”plywood are connected to the eyebolt with 3/8” nuts.
A 1/16” piece of aircraft cable attaches to the eyebolt with the help of a wire compression sleeve. During training, this weight-stand with the weights hang over a horizontal pulley attached to the edge of a workbench. The aircraft cable continues to a set screw shaft coupler, which connects the aircraft cable to the SMA wire. The SMA wire, which is parallel to the workbench surface during training, is attached to another set screw shaft coupler. This coupler is then wrapped in electrical tape to insulate it and is clamped tightly with a vice that is bolted into the table. Three power sources with constant current/varying voltage are wired in parallel and connected to each end of the wire. On the workbench, directly below the wire, a piece of paper next to a ruler was taped down. With each expansion and contraction cycle, the different lengths of the wire were recorded, making it possible to know when to stop the thermocycling procedure. A full set-up of the training procedure is seen in Figure 18.
Figure 18. The set-up of the SMA wire training process. As seen, weights are supported by a weight-stand, hanging over the edge of the work bench supported by a horizontal pulley. Set crew couplers connect aircraft cable to the wire, and allow the gripping of the wire by a vice bolted to the table. Three current sources supply the current necessary to heat the wire beyond its transition temperature.

Results

Nosecone Outer Shell Prototyping

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Conclusions and Recommendations

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The complete assembly of this system was not possible due to a lack of funding to pay for a metal 3D printing company to print the outside geometry out of aluminum. Several 3D printing companies with metal 3D printers were contacted, but they were unable to make a complete donation of the parts at this time. When the nosecone shell pieces are printed, this design will be assembled and launched on a rocket that is projected to achieve velocities over 1.2 Mach. Such a rocket will be launched by the Akronauts Rocket Design Team, at the University of Akron, at the Spaceport America Cup in New Mexico in the future.

In the future, SMA wires will also be considered for use in other systems within the high powered sounding rockets, built by the Akronauts. Upcoming projects for which this material may be useful for include airbrakes and canted fins for spin induced stabilization. In industry, the use of shape memory alloys is also projected to increase across multiple different fields, as more individuals become familiar with SMAs and their potential.
Acknowledgements

Special thanks goes to Santo Padula, PhD., a materials specialist who work with SMAs at the NASA Glenn Research Center. Santo was instrumental in facilitating a deeper understanding of SMAs, which was necessary for this project. Santo also helped instruct on the procedures necessary to train the SMA wires. A thank you also goes out to Shane Benner, for his expertise in electronics. Shane provided critical guidance for the set-up of the power sources use to help with the SMA training procedures.

Works Cited


