Bending Flight: Optimizing Aircraft Stability in Wings

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Introduction

For decades, the aviation industry has faced a longstanding, persistent issue: turbulence. From 1979 to 2020, the duration of severe turbulence- the type capable of causing injuries and significant structural damage- has increased by 55% in commercial aircraft (Prosser et al., 2023). Since then, turbulence-related injuries have increased by 52% from 2019 to 2023, highlighting it as a prevalent issue to this day (Potter, 2024). According to the National Center for Atmospheric Research, due to the significant damage it incurs, US airlines allocate $150-500 million annually to account for turbulence-related accidents and incidents (NCAR, 2024). Therefore, aircraft designs that prioritize safety and performance are needed now more than ever. This brings focus to the concept of “morphing wings”. According to communications specialist at Purdue University Jared Pike, morphing wings refer to aircraft wings that can “change their shape and control their flight” (Pike, 2022). To function, these wings rely on using materials capable of flexing and morphing accordingly. While most morphing wings utilize carbon fiber or latex, there are still questions regarding whether or not there may be a more effective, efficient material embodying similar morphing characteristics (Turbli, 2023). This has turned attention to an emerging material in the field- shape-memory alloys. Shape-memory alloys (SMA) are metals that have the unique ability to “retain their previous form” after being exposed to certain stimuli such as “thermomechanical or magnetic variations”, hence the name “shape-memory” (Jani, 2023). After being discovered in 1932, the term “shape-memory” appeared in 1941 to describe the nature of these metals, specifically nickel-titanium (NiTi) as it was one of the first metals to be discovered with this characteristic (Jani, 2023). Initially being seen primarily in naval applications, the use of SMA’s expanded to various fields such as consumer products and fashion, but a more significant use can be seen emerging in aviation as its unique behavior serves as a hotspot for major innovations in the field such as morphing wings (Jani, 2023). However, there is limited research on the application of SMA's in morphing wings, despite numerous theories calling out their potential to revolutionize aircraft design. Therefore, this paper aims to explore the possibilities of utilizing SMA's in morphing wings to reduce potential instability in commercial aircraft structures, shedding light on their future developments and contributions to aviation.

Literature Review

Advancements of Morphing Wings in Aviation

To fully understand the effects of morphing wings in aviation, it's essential to explore its advancements and compelling benefits. In the article "How Much Can an Airplane Wing Bend?", researchers acknowledge such wings as a "spring" helping to "[reduce] the sensation of turbulence for passengers" (Turbli, 2023). An example would include the Boeing B787-9 as it makes use of the morphing wings concept to provide a stable, comfortable flight for passengers. However, rather than SMA's, it's comprised of carbon-fiber composites due to their thin and highly flexible characteristics (Turbli, 2023). Similarly, Seth Price, a lab associate at New Mexico Tech, also highlights the benefits morphing wings can have on improving passenger comfort by reducing vibrations but addresses the potential for SMA's to do it more effectively as it could easily "adjust the rigidity of the wings" and provide more flexibility when flying (Price, 2023). Alina Rudani, a writer for the Concordia Business Review, also takes on the stance that morphing wings cause less stress and discontinuities in flight and takes it further by addressing how that could result in increased lift and airspeed (Rudani, 2023). However, unlike Price, her studies don't consider the application of SMA's.

The Practicality of Morphing Wings in Aviation

Given the immediate short-term benefits that morphing wings provide regarding passenger comfort, the same profound benefits can be seen in the long term as well. A study conducted by Dr. Emre Ozbek, a Professor at Eskisehir Technical University, focused on the modification and optimization of 3D material-based morphing wings and revealed an increase in feasibility for long-term aircraft designs (Ozbek et al., 2023). Drawing upon that same idea, Dr. Alexsteven Dharmdas, Professor at KLE Technological University, states that the effect of such feasibility can "minimize environmental impact" as it requires less fuel and power for these wings to function (Dharmdas et al., 2023). Especially as "the cost of jet fuel has increased by over 149%" compared to previous years, knowing that morphing wings "[reduce] fuel usage" helps to address these rising costs and CO2 emissions (Rudani, 2023). Therefore, the feasibility and efficiency that morphing wings provide lead to reduced costs and improved environmental conditions by "[reducing] the aviation industry's negative impact on global warming" (Rudani, 2023). By recognizing the practicality and emerging significance of morphing wings in aviation in both the short and long term, it becomes evident that their feasibility and efficiency make them indispensable in improving global and local conditions in the industry.

Current Research and Applications of Shape-Memory Alloys

In the context of morphing wings, interest in the application of SMA's is notably high given the substantial potential these unique materials hold for advancing the field of aviation. In the article written by Seth Price, he acknowledges the potential for SMA's to modify aircraft wings successfully to reduce noise pollution and instability given their ability to bend back and forth without much effort (Price, 2023). In a similar paper written by Jaronie Mohd Jani, research conducted strengthens the same idea by acknowledging the major deformation recovery SMA's provide as well as less instability from dampened vibrations, however, this understanding is gained from placing the SMA's inside of the aircraft wings as actuators rather than outside as morphing wing material. Regardless, the study helps in exemplifying the practical implications of SMA's. Furthermore, in a paper written by Faisal Mahmood, a Professor at Harvard Medical School, a broader perspective of SMA applications is acknowledged as the study conducted explores the potential for SMA's to reduce carbon emissions from aircraft and improve efficiency (Mahmood et al., 2023). Knowing that SMA's hold potential benefits similar to those seen in morphing wings themselves such as reduced carbon emissions and vibrations, the idea of implementing them into morphing wings is highly supported. However, while these studies provide a comprehensive view of how SMA's may contribute to further advancements in aviation, research is needed to test these theories and the idea of SMA's as a material type for morphing wings.

Limitations and Considerations of Shape-Memory Alloys

One such reason for a lack of research may be the potential downsides SMA's possess. In the paper written by Faisal Mahmood, the study conducted also makes use of a hazard assessment of SMA morphing wings, revealing potential risks concerning the longevity and structural integrity of the material (Mahmood et al., 2023). In a paper written by Santosh Sampath, an Assistant Professor at the Sri Sivasubramaniya Nadar College Of Engineering, an explanation for such a short span is considered by addressing varying environmental factors that can affect SMA's corrosion resistance, hence making it weaker over time and more susceptible to breaking (Santosh et al., 2023). However, in the paper written by Farhad Sabri, while limitations of longevity, deflections, and resistance are considered, a proposed solution is offered as well by providing a study considering new strategies to enhance the durability and effectiveness of SMA's through algorithm formulation (Sabri, 2023). Making use of aeroelastic algorithms implemented in a software or model can make it easier to understand the ideal characteristics required to reduce the torsional stiffness and twist angles of SMA's, making the possibility of structural failure occurring minimal (Sabri, 2023). Methodology-wise, these studies all provide a similar purpose in analyzing the longevity of SMA's although they do it under varying conditions. But understanding the challenges that SMA's may encounter is essential in comprehensively assessing their role in the future of aviation, and serves as a strong foundation for devising future methodologies implementing SMA solutions effectively while accounting for such limitations.

Exploring the Application of Shape-Memory Alloys in Morphing Wings

Considering the research done on the existing body of knowledge regarding morphing wings, it is evident that much of the research focuses mostly on benefits such as increased lift or decreased turbulence while using traditional materials such as carbon fiber or latex in their respective studies. In contrast, the emerging application of SMA's in morphing wings has received limited attention, highlighting a gap where the potential of SMA's achieving more effective results remains unexplored. For instance, while researchers have discussed the advantages of morphing wings in terms of passenger comfort and fuel efficiency, they have yet to test and consider the characteristics of SMA's which may have the potential to revolutionize aircraft design. My research aims to answer the question of the extent to which the application of SMA's in morphing wings can reduce potential instability in commercial aircraft structures. The significance of this research extends beyond the aviation industry as it has the potential to directly impact the overall flying experience for passengers through more comfortable and safe flights. Furthermore, the application of SMA in morphing wings has the potential to significantly reduce fuel consumption and lower costs, benefiting both airlines and travelers while contributing to a global impact through reduced carbon emissions. Thus, bridging this gap in existing research on SMA technology not only serves the aviation industry but also aims to make a meaningful impact on the lives of individuals, improving their travel experiences and contributing to a greener and more sustainable future.

Method

Overview

The chosen methodology for this research was the experimental design approach. By recognizing the need to establish correlations between independent variables such as material types and their corresponding dependent variables of lift generation and instability, I determined the experimental design method to be the most effective for analyzing these relationships. Additionally, with the focus of the research being specifically on commercial aviation structures and the utilization of materials to reduce instability, the scarcity of data on this particular aspect encouraged the decision to design and conduct an experiment in which I would be able to collect that necessary data that was otherwise unavailable.

The methodology comprised four key steps: 1) Designing airfoil models utilizing styrofoam, SMA Nitinol wires, and ¼ corrugated cardboard, 2) establishing an experimental setup featuring a Vornado 660 circulator fan, digital scale, and ruler to ensure controlled experiments, 3) finding loss in mass and fluctuations at different fan speeds for each material, and 4) recording data effectively to analyze correlations between the various airfoil materials and performance indicators.

Experimental Set-Up

In this study, styrofoam was used to design the airfoils that would replicate the wing structure of commercial planes. Airfoils are defined by NASA as the cross-section of a plane wing, designed to have air flowing around it (NASA, 2023). By making use of airfoils in my experiment, I would therefore be able to effectively simulate conditions in which I would be testing the performance of commercial plane structures. The airfoil shape I went with was cambered as it's one that's been "widely adopted into commercial aviation" due to its curved top and flat bottom optimizing the generation of lift when flying (Wilson, 2021). The airfoil was made of styrofoam as it was easily accessible, cheap, stiff, and lightweight- making it a more reasonable choice compared to other regularly used materials such as aluminum, steel, or wood. After tracing the cambered shape, I cut through the styrofoam using a hot wire to ensure precise and smooth edges. The airfoil dimensions were 3″ x 2″ x 1.25″ as it was exactly ¼ of the styrofoam block. Half of the excess styrofoam was then used as the base for the setup with wooden skewers attached in the center of both long sides. The purpose of the base was to attach the airfoils to a flat surface to allow the wind to hit the airfoil directly at one center point. Paper clips were then attached to the skewers using elastic rubber bands with one wire placed out to attach the airfoil. These household materials were used because they were easily accessible and effective in simply attaching the airfoil to the base and ensuring freedom of movement with the thinness of the paperclip wire. Ensuring this freedom of movement would be essential in allowing the airfoil to move up and down as needed, similar to morphing wings, when hit with the wind force from the Vornado fan. The Vornado fan would be used to simulate the actions of the airfoil's flight once hit with air being blown around it. Additionally, a digital scale would be placed underneath the base structure with the airfoil to measure the mass of the airfoil before and after being subjected to the wind force. The purpose of measuring the mass during the experiment would be to observe the amount of mass lost as that would indicate the amount of lift being generated. This approach towards measuring lift is similar to the paper "Development of a

Robust Wind Tunnel Balance for Wingsuit Aerodynamic Testing" where researchers used a lift sensor beneath a wind tunnel to measure the reduction of mass in an airfoil as the amount of lift being generated (Sestak, 2015). However, unlike this study, I did not make use of a wind tunnel due to a lack of accessibility and financial constraints. Additionally, while I was looking at reduced instability in commercial aircraft structures, that study focused on improving wingsuit designs. The final step in my set-up was adding a ruler alongside one of the wooden skewers attached to the base to measure the amount of fluctuations occurring from the airfoil once hit with the wind. The purpose of doing so would be to observe the amount of instability occurring as fluctuations indicate a lack of stability. In the paper "Experimental Study on Transition of Dynamic Airfoil in Pitching Oscillation", researchers measured the number of oscillations occurring by recording the number of times the airfoil tapped surfaces below and above it to observe indications of instability (Wei et al., 2023). The paper employed a similar idea by recording fluctuations to relate to a lack of stability however it differed in its approach by using wall borders on either side rather than a ruler, and attempted to answer questions regarding the effect of transition periods on airfoil performance rather than reducing instability. See Appendix for an image of the completed experimental setup.

Procedure

To get a more accurate, comprehensive collection of data, I conducted 30 trials- recording the initial and final mass of the airfoils after turning on the Vornado fan. The first ten trials were with the airfoil on its own, the next ten were with cardboard, and the final ten were with SMA Nitinol wires. Serving as the control group, the airfoil on its own would set a baseline that I could then compare the results of the experimental group to. The experimental group would be the airfoil with the added materials- cardboard and SMA wires. The purpose of using cardboard was to simulate the utilization of conventional materials in this experiment as most commercial aircraft use latex or carbon fiber when designing their structures. However, due to a lack of accessibility and financial constraints, I used ¼ corrugated cardboard as it employed similar characteristics of being lightweight and having a strong strength-to-weight ratio due to its high stiffness. Additionally, the use of the SMA wires would directly answer my research question about their use while comparing them to not only the control group but another experimental group as well. I used SMA Nitinol wires specifically due to their affordability and high availability. To account for the varying wind speeds that aircraft are subjected to when flying, I split each set of 10 trials into 5 with the fan at the lowest speed and 5 at the highest speed. This would simulate more realistic weather conditions as it's highly unlikely that aircraft face one consistent speed.

Lift Generation

The importance of measuring the amount of lift being generated by the airfoils would be essential in understanding the effectiveness of its performance with different materials to further understand the relationship between material usage and aerodynamic stability. After connecting the airfoil to the paper clip wire, I recorded the initial mass from the digital scale underneath the base. I then turned on the Vornado fan to the lowest setting and waited for 10 seconds before recording the final mass after being hit by the wind force. I then repeated this two more times before changing the fan speed to the highest setting and following the same procedure for 5 more trials. After completing the 10 trials for the control group, I then attached strips of cardboard with tape to the airfoil surface- covering the main central points being hit with the wind force. This included the outermost edges and direct center of the airfoil. This would allow me to observe differences in the airfoil's performance with different materials. Although cardboard wasn't an ideal material for testing conventional materials, it was still effective in providing a general comparison to stiffer materials. I followed the same process as before- conducting 10 trials for the cardboard and recording initial and final mass values. Finally, the last 10 trials were completed with the SMA Nitinol wires attached in the same manner as the cardboard strips for consistency. After completing this collection of data, to determine the amount of lift being generated in each instance with a specific material and wind speed, I subtracted the final mass value from the initial mass value to find the amount of mass lost and converted to lift.

Fluctuations

The next portion of the data collection process included recording the fluctuations occurring from the airfoil. Using the ruler in the set-up, I measured the change in centimeters from the airfoil's equilibrium position to its highest or lowest point while being hit by the wind force from the Vornado fan. Centimeters were chosen due to their precision in quantifying the subtle displacements of the airfoil as it moved. This was recorded in a table as (high-low) in cm to keep the data more organized and easy to analyze. While following the same procedure with 10 trials for each group, I noted the fluctuations for each instance and material type before finding the average fluctuation values by adding the high and low values and dividing by 2. The purpose of doing so would be to effectively see which material types resulted in the greatest fluctuations from their equilibrium position. Knowing this would be essential in understanding a material's contribution to instability, as evidenced by fluctuations.

Results

The following tables include the data I collected from each trial during my designed experiment for the styrofoam airfoil on its own, cardboard, and shape-memory alloy (SMA) Nitinol wires. Yellow represents the control group with no additional materials, blue represents an experimental group with cardboard, and green represents an experimental group with SMA wires. The data includes the initial mass, final mass, mass lost, and fluctuations recorded for each different material type and fan speed. Each table is followed by an interpretation of the data in regard to the effectiveness of the airfoil performance.

Table 1: Low fan speed, Styrofoam						
Trial	Fan Speed	Initial Mass (g)	Final Mass (g)	Mass lost (g)	Fluctuations (cm)	Material
1	Low	77	72	5	2-2	None
2	Low	77	73	4	1.75-1.90	None
3	Low	77	74	3	1.90-2	None
4	Low	77	73	4	1.60-1.8	None
5	Low	77	73	4	1.70-1.85	None

Table 1 serves as the control group for low fan speeds in the experiment. The data I collected from the styrofoam airfoil on its own sets the benchmark for the low fan speed experimental results. The range for the mass lost was from 3-5g and the fluctuations were from 1.6-2 cm.

Table 2: High fan speed, Styrofoam						
Trial	Fan Speed	Initial Mass (g)	Final Mass (g)	Mass lost (g)	Fluctuations (cm)	Material
6	High	77	70	7	1.2-1.5	None
7	High	77	68	9	1.2-1.3	None
8	High	77	68	9	1.1-1.2	None
9	High	77	66	11	1.0-1.2	None
10	High	77	69	8	1.1-1.3	None

Table 2 displays the data I collected from the next control group set for the high fan speeds in the experiment- using the styrofoam airfoil to set the benchmark for the high fan speed experimental results. The range for the mass lost was from 7-11g and the fluctuations ranged from 1.0-1.5 cm. There is a significant difference in the mass lost and fluctuations caused between both the high and low fan speed airfoil results in Table 1. This indicates a relationship between fan speed and lift generation as the mass lost increases with higher fan speeds and is converted to lift.

Table 3: Low fan speed, Cardboard						
Trial	Fan Speed	Initial Mass (g)	Final Mass (g)	Mass lost (g)	Fluctuations (cm)	Material
1	Low	80	73	7	1.45-1	Cardboard
2	Low	80	72	8	1.45-1.5	Cardboard
3	Low	80	74	6	1.5-1.7	Cardboard
4	Low	80	73	7	1.6-1.75	Cardboard
5	Low	80	74	6	1.4-1.6	Cardboard

Table 3 shows the data I collected from the cardboard airfoil with low fan speed. The data ranges in mass loss from 6-8g and fluctuations from 1.4-1.75 cm. Compared to Table 1, the range for mass loss is greater and the fluctuation range is smaller. This indicates that with additional materials such as cardboard, the airfoil performance is affected by generating more lift and reducing instability as more mass is converted into lift and fewer fluctuations affect stability.

Table 4: High fan speed, Cardboard						
Trial	Fan Speed	Initial Mass (g)	Final Mass (g)	Mass lost (g)	Fluctuations (cm)	Material
6	High	80	71	9	1.1-1	Cardboard
7	High	80	69	11	0.5-0.8	Cardboard
8	High	80	71	9	0.85-1	Cardboard
9	High	80	70	10	0.6-0.8	Cardboard
10	High	80	69	11	0.75-0.85	Cardboard

Table 4 shows the data I collected from the cardboard airfoil with high fan speed which ranged in mass loss from 9-11g and fluctuations from 0.5-1.1 cm. Compared to Table 2, the ranges are similar for the mass lost although cardboard is greater by one gram. However, the fluctuations differed for both groups as the cardboard had a smaller range than the control group. This indicates a small improvement in lift generation but a great difference in instability reduction. Additionally, it strengthens the idea that cardboard as an additional material affects the performance of the airfoil.

Table 5: Low fan speed, SMA Nitinol Wires						
Trial	Fan Speed	Initial Mass (g)	Final Mass (g)	Mass lost (g)	Fluctuations (cm)	Material
1	Low	82	74	8	0.5-0.7	SMA
2	Low	82	73	9	0.7-0.9	SMA
3	Low	82	72	10	0.5-0.8	SMA
4	Low	82	73	9	0.6-0.8	SMA
5	Low	82	73	9	0.7-0.9	SMA

Table 5 displays the data I collected from the SMA airfoil with low fan speed which ranged in mass loss from 8-10g and fluctuations from 0.5-0.9 cm. Compared to Table 1, the control group, there is a significant difference between the mass loss and fluctuation ranges. Almost all the fluctuations recorded are under a centimeter for the SMA, unlike the control group with all values closer to two centimeters. Additionally, the mass lost values are almost twice those of the control group. Even when compared to cardboard in Table 3, the fluctuations are significantly less and the mass lost is still greater by almost 2-4g. This indicates that SMA’s are highly effective at improving performance when compared to the control and cardboard groups.

Table 6: High fan speed, SMA Nitinol Wires						
Trial	Fan Speed	Initial Mass (g)	Final Mass (g)	Mass lost (g)	Fluctuations (cm)	Material
6	High	82	70	12	0.3-0.5	SMA
7	High	82	71	11	0.4-0.5	SMA
8	High	82	69	13	0.2-0.4	SMA
9	High	82	70	12	0.2-0.5	SMA
10	High	82	69	13	0.3-0.4	SMA

Table 6 displays the data I collected from the SMA airfoil with high fan speed which ranged in mass loss from 11-13g and ranged in fluctuations from 0.2-0.5 cm. Compared to Table 2, the ranges for mass loss are much greater and the ranges for fluctuations are much smaller. The same improvement is shown when compared to Table 4. Additionally, it strengthens the idea of a relationship between fan speed and reduced instability as the fluctuations are reduced and lift is increased when compared to the SMA airfoil with low fan speed in Table 5. Almost all mass loss values for the SMA with high fan speed are greater than ten grams, while the SMA with low fan speed has ten grams or less.

Table 7: Averages of each category						
	Low, None	High, None	Low, Cardboard	High, Cardboard	Low, SMA	High, SMA
Average Mass Lost (g)	4.000	8.800	6.800	10.00	9.000	12.20
Average Fluctuations (cm)	1.850	1.210	1.495	0.825	0.710	0.370

Table 7 displays the averages of each category which I calculated by summing the results of each trial and dividing by five as each category had five trials conducted. The table includes the averages for mass loss and fluctuations as those are the best indicators of airfoil performance.

The results from this table indicate that the airfoil with SMA had the best performance as it had the most amount of lift generated and the least amount of fluctuations across all trials and conditions. The cardboard also improved the performance of the airfoil, although it wasn't as effective as the SMA as shown in Tables 3 and 4. The airfoil on its own had the least effect in reducing instability as the values for both mass loss and fluctuations were significantly weaker than both experimental groups as shown in Tables 1 and 2.

Discussion and Analysis

The results from the shape-memory alloy (SMA) experiment can be categorized into three main trends. First, external forces play a vital role in the performance of an airfoil, affecting stability and lift generation. Second, the specific materials utilized play a role in the degree of improvement, with certain materials exhibiting better attributes than others. Third, the greater the amount of lift generated, the less instability that occurs. I decided to examine the outcomes of the SMA experiment by creating bar charts to allow for a clear visualization of the material's influence within each group. Figures 1 and 2 below represent the groups for styrofoam in yellow, SMA Nitinol wires in green, and cardboard in blue.

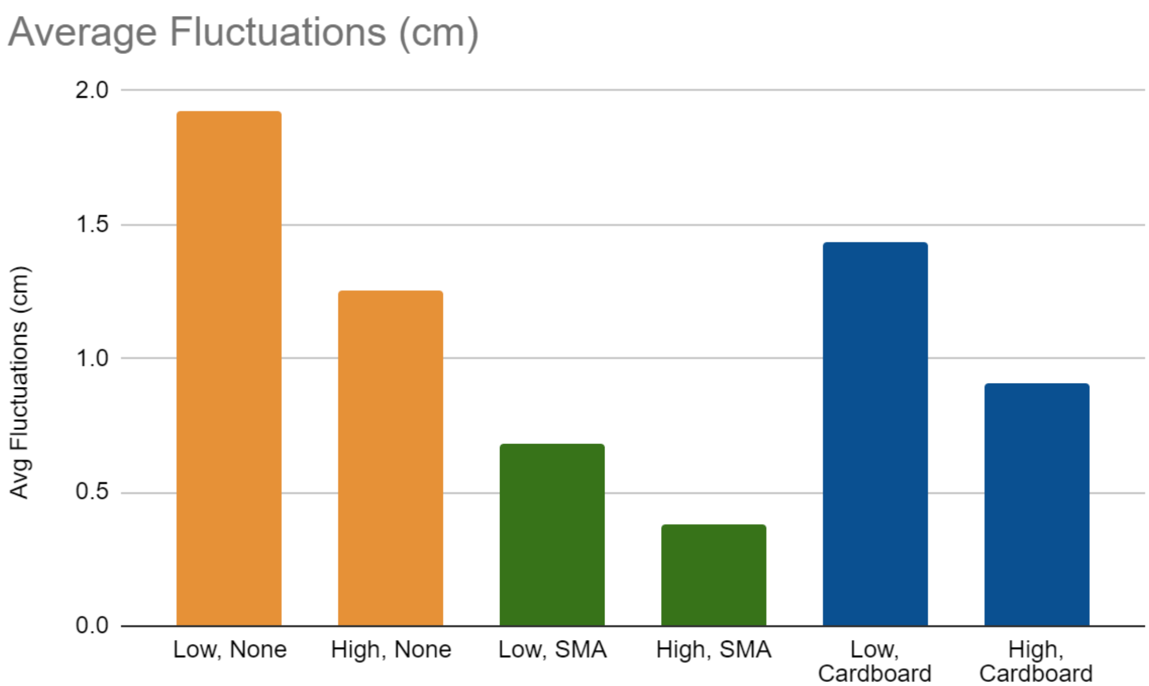

Figure 1. Average fluctuations of materials and conditions

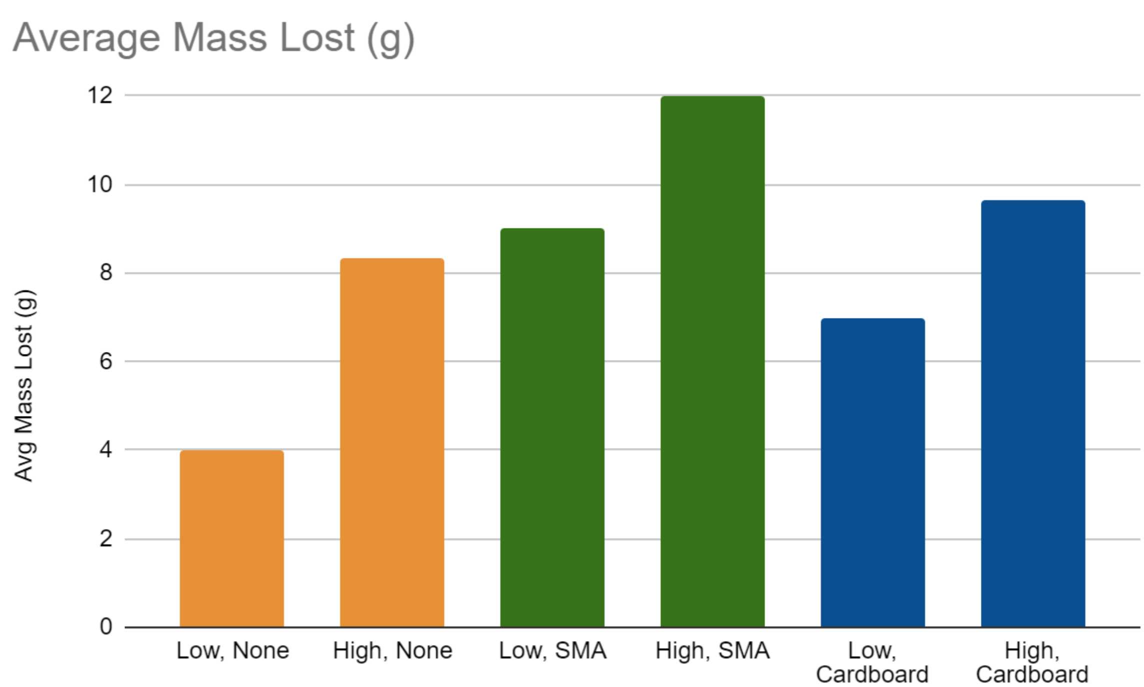

Figure 2. Average mass loss of materials and conditions

Evidence suggests that the first trend of external forces affecting performance holds, as each material demonstrated improved results with higher wind speeds in comparison to lower ones. As shown in Figure 1, each group reduced their fluctuations by at least 0.3 cm when subjected to higher wind speeds, which indicates greater stability. Figure 2 on the other hand, shows how this created an increase in mass lost by at least 3g, which indicates more lift being generated. This is likely attributed to the fact that greater wind speed "creates greater velocity difference over the wings…[increasing] lift forces" (Shaw, 2021). Additionally, the results highlight the second trend, where the significance of SMA on performance is greater, in terms of both stability as shown in Figure 1, and lift generation as shown in Figure 2. Due to the SMA possessing qualities of morphing and not resisting applied forces, it makes sense as to why it would be much more effective than cardboard and styrofoam at producing better results. This aligns with my initial hypothesis of SMA's being the most effective in reducing instability due to their lightweight and flexible nature. Seth Price's findings, as mentioned earlier, are similar to my findings as they concluded that SMA's possess the potential to effectively modify aircraft wings, reducing instability due to their ability to morph with minimal effort (Price, 2023). Although further tests have yet to validate these theories, the concept is expected to be effective. My research strengthens that theory by demonstrating that SMA's are indeed capable of reducing instability, as evidenced by their reduced fluctuations and increased lift generation.

To display a comprehensive analysis of all categories, encompassing both fluctuations and mass loss, I created a bar chart with two distinct colors. In Figure 3 below, blue represents the average mass loss values while red represents the average fluctuation values.

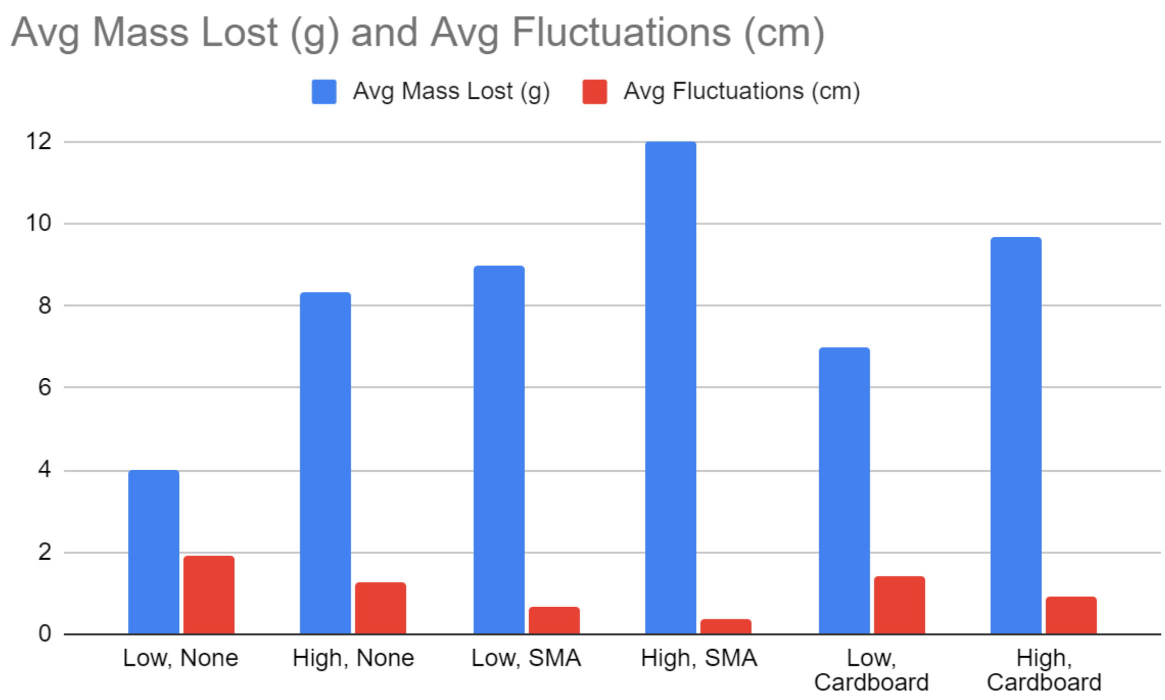

Figure 3. Average mass lost compared to average fluctuations

Figure 3 highlights the final trend which indicates an inverse relationship between mass lost and fluctuations created. As the value of one factor increases, the other decreases. This makes sense as increases in lift reduce the magnitude of unbalanced forces acting on the airfoil, leading to smoother performance. These findings are similar to those found by Dr. Demetri Telinonis, a professor at Virginia Tech, who claimed after conducting a series of wind tunnel experiments that “[increases] in lift… [reduce] the induced drag” which causes instability (Telionis, 2005). This inverse relationship also simplifies the analysis of the extent to which SMA’s can reduce instability- which relates to my research question. Examining fluctuations alone isn’t sufficient enough to grasp the full extent of instability reduction, as lift generation provides another factor essential for understanding the degree of performance improvement with stability, given its inverse relationship with it. Styrofoam had the least effect in reducing instability, followed by cardboard, then SMA's- which were able to do so to a high extent. This is due to the SMA having the greatest amount of mass lost and the least amount of fluctuations since a lack of fluctuations indicates greater stability from the amount of lift generated from the mass lost.

Limitations

In the SMA experiment, I only made use of cambered-shaped airfoils which is the cross-section shape most commonly used in commercial aircraft. However, there is a small percentage of commercial aircraft in the field that use wings with symmetrical or reflex-cambered cross-sections. Therefore I cannot extend the results of my experiment to all commercial aircraft, but only those with cambered wing shapes.

Future Research

Considering that my experiment made use of non-conventional materials and conditions that didn't fully replicate actual flight scenarios, there is a need for further research to mitigate these sources of error. One potential improvement would include utilizing wind tunnels instead of fans to more accurately simulate airflow conditions experienced during flight testing. Additionally, making use of materials such as carbon fiber and latex, which are more representative of those commonly used in aviation, could improve the applicability of my findings. Several airfoil shapes can also be incorporated to encompass all the different types found in commercial aircraft structures. This would enable a more comprehensive analysis of how different airfoil shapes may interact with specific materials under varying conditions. This would also allow researchers to understand the performance characteristics and potential advantages or limitations associated with each design. Moreover, the next steps would include investigating the scalability of SMA technology for commercial aircraft and looking into their potential cost-effectiveness in manufacturing processes. This would be essential in creating a more practical implementation of SMA's in the aviation industry.

Implications

Understanding the impact of SMA's on reducing instability and enhancing airfoil performance can extend to commercial aircraft structures with cambered wing shapes, as airfoils serve as crucial components for testing. Exploring the effectiveness of SMA's in reducing instability holds promise for revolutionizing aircraft design practices. This research serves a crucial purpose in identifying solutions for enhancing flight safety for both airlines and passengers. This is especially important considering that conventional wings in commercial aircraft can weaken over time, increasing susceptibility to damage (Santosh, 2023). By reinforcing the theory of SMA's in aircraft structures to address such concerns, my research offers a potential solution. Moreover, as SMA's demonstrate the capability to resist forces and improve lift generation given their flexible nature, they can contribute to global efforts working to mitigate carbon emissions stemming from fuel usage, by reducing fuel consumption. With decreasing fuel consumption, airlines can make significant cost savings, which could also reduce ticket prices for passengers, making air travel more accessible to a wider demographic. As air travel continues to grow as a mode of transportation, the adoption of technologies such as SMA's can make it safer and cost-efficient by minimizing maintenance requirements and extending the lifetime of an aircraft. Such advancements contribute to more sustainable efforts by fostering more economic growth and innovation while reducing environmental impact.

Conclusion

With increasing concerns regarding structural stability in modern aircraft designs, it's essential to find plausible solutions meant to mitigate the otherwise disastrous effects of instability in flight. This highlights the need for further research for innovations in the field of aviation which is what this study delves into. Through experimentation, the SMA exhibited significant improvements in both lift generation and stability compared to materials with similar characteristics to those of conventional materials found in the industry. These findings emphasize the potential of SMA technology to revolutionize aircraft design, offering promising solutions to longstanding challenges in aerodynamics and flight safety regarding instability.

As SMA technology continues to evolve, it's through further research and development that its full potential can be recognized in the field of aviation. The advancements of SMA's could lead to more sustainable aircraft structures, reducing maintenance costs and extending the lifespan of commercial aircraft through their properties of being flexible and lightweight. This not only lowers operational costs for airlines but also contributes to environmental sustainability by reducing the need for frequent structural repairs. Therefore, with the utilization of SMA technology, the aviation industry is pushed towards a new era of safer, more eco-friendly, and economically viable air travel- shaping the future of flight.

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Appendix

Final Experimental Setup

Note: This shows the airfoil on its own without any additional materials attached.