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Aircraft Innovation: A Look at Morphing Wing Technologies to Improve Fuel Efficiency

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***Abstract*—** This paper explores the possibility of improving fuel efficiency through morphing wing structures on unmanned aerial vehicles (UAVs). Based on the quantitative data of battery level and velocity of the UAV in a set time interval with and without morphing structures, conclusions were made on the effectiveness of these structures, and future directions were discussed. The results showed that morphing structures are beneficial for fuel efficiency through the correlation made with battery level and they also improve aircraft performance as seen by the improvement in the velocity of the UAV.

***Keywords*—** aircraft, fuel efficiency, UAVs, improvement.

LITERATURE REVIEW

The inspiration for the airplane wing can be seen as the bird wing. While the aves wing structure was the inspiration for the design, the function is now somewhat shifting towards the oscillating motion of the bird wing. That is the motion that fascinated scientists and is something that has yet to hit the aerospace industry with commercial aircraft. Airborne animals such as birds can control their aerodynamic forces by changing their wing structures throughout their flight time which is something that aircraft cannot do yet (Ozbek, 2023). This motion can be defined as morphing structures when implemented in aircraft. Ever since the bird's motion inspired the airplane, it has evolved to look quite different compared to birds for obvious reasons. For example, airplanes do not land and take off in the same way as they need a lot of space to exercise those maneuvers. However, morphing wing structures can make modern aircraft even more similar to birds by introducing a wing that changes shape during flight. These structures can resolve the ongoing issue in the airplane wing that makes airplanes less efficient than aerodynamic animals such as bats and birds. Some of the common terms that will be used in this paper are the words "morphing" and "Unmanned Aerial Vehicles". Morphing is a term used for describing something that changes constantly. In the context of airplanes, it would be the changing wing structures throughout the flight. Morphing wing structures can make aircraft more efficient by adapting to external conditions (Zhang, 2023). The latter term, Unmanned Aerial Vehicle or UAV, is critical in the aerospace industry as it is widely used for testing within the field. These vehicles are used for testing aeronautical procedures such as the morphing structures that are explored in this paper (Zhang, 2023, p.1). Although these vehicles undergo significant amounts of dangerous testing, they are risk-free as they do not endanger humans (Zhang, 2023). Other common applications of the UAV are photography, agriculture, and even advanced communications. As Weizhi Zhong states in his paper on using UAVs for 6G communication, "UAVs have emerged as a promising technology that can fulfill diverse requirements (Zhong, 2024). This paper utilizes the UAV as a model for testing purposes without posing any risk to a pilot or those on the ground.

Pre-existing research regarding morphing wing structures shows different types of testing on these structures using various methods. One example is seen in Sijia Jia's article "Wind Tunnel Test od 3D-Printed Variable Camber Morphing Wing", which performs testing using ground procedures and wind tunnel tests to see how morphing structures affect various aircraft maneuvers such as sideslipping, airflow over the wing, and overall balancing of the aircraft. Jia's research serves as the foundation for the style of research performed in this paper as it studies a similar component of the aircraft: the wing. The major problem that persists worldwide is that airplanes are one of the most polluting vehicles in the world, even in this modern era of transportation. Based on Jia's study, the wing is a major component of the aircraft that can be modified and installed with morphing wing structures to test the effectiveness of the structures in various aspects. In this paper, morphing wing structures will be utilized to observe their effectiveness in reducing the environmental impact of modern aircraft. The major effect on the environment by aircraft is caused by the large amounts of fuel consumed by modern aircraft. For example, Concorde, discontinued in 2003, consumed more fuel during its taxi than an average car does in a year. Although the supersonic jet was discontinued for the reason of high prices of jet fuel, not much attention was paid to the environmental impact of its excessive fuel consumption. This problem has not been improved in present-day aviation as the Airbus A320 is the most commonly used aircraft worldwide but also takes a toll on the environment with its high fuel consumption and carbon emissions, which only worsens the aerospace industry's environmental footprint. A study done in 2001 by Boeing and NASA engineers David Daggett, Gerhard Seidel, Robert McKinley, and Robert Plencner explores different experiments used to reduce fuel consumption, but do not include morphing structures. Their "concept" airplanes or different UAVs used for their five airplane concepts to improve fuel efficiency included: Improving the propulsive efficiency of the engine, using a highly efficient turbofan in the engine, and a blended-wing body among others (Daggett, 2001). It is important to note that there have not been any significant changes to the functioning of aircraft since 2001 when Daggett's research was published. The only major changes have been to the computers within the aircraft such as autopilot and landing assist technology which help the pilot fly. However, none have been directed at protecting the environment or significantly decreasing fuel consumption. Potentially, morphing wing structures can aid in solving this major issue of excessive fuel consumption. This raises the question: how can morphing wing structures be implemented in aircraft to improve fuel efficiency without compromising performance?

The major gap in this research is that morphing technology has not been tested to reduce the environmental impact of aircraft which is what this paper covers. While there have been numerous studies involving morphing structures at the university and higher levels of research, none have connected morphing structures and fuel consumption highlighting a significant gap in this research. Researchers in the past have struggled to completely implement advanced morphing structures to aircraft stating that "Installation of conventional flight control actuators generally requires rigid mounting structures and a firm hinge line to ensure control precision and avoid control binding. It is a challenge to meet such design requirements when applying a conventional control mechanism to an inflatable structure" (Zhu, 2023, p.1). The gap can be addressed using case studies and experiments as seen in other academic articles which may include topics in proximity to the one this paper covers. Through initial research on this topic, a hypothesis has been determined: morphing wing structures will increase fuel efficiency in aircraft to a large extent while maintaining current performance standards and the skies will slowly improve toward greenery in the future.

METHOD

The design of this research ensures that the research done will fill the gap in the body of knowledge as it attempts to combine information from secondary sources and experiments to gain the missing information. For the quantitative research, longitudinal studies were performed which tracked the progress of the research over a long period. In this case, the status of the morphing structures was observed over set periods and conclusions were made on their effectiveness. Then, decisions were made on whether the construction or placement of the structures needed to be changed to provide the most effectiveness. This was essential in this research as the morphing structures were improved based on their accuracy during testing. Furthermore, for qualitative research, case studies were performed to compare the results of various experiments performed with groups such as the control without equipped morphing structures and those that had the morphing treatment applied. This type of design fits in the community of aerospace development and innovation as it focuses on improving a certain structure of the aircraft for the future and benefitting the world and its people. The information was collected using different calculations, tests, and methods used to analyze the morphing structures. This research will focus greatly on quantitative data as numbers and calculations are essential to the result produced in this study. There are major dependent and independent variables present in this study which greatly influence the result. The independent variable is the application of morphing wing technology on the aircraft models or the flying machine itself. The dependent variable is whether or not the fuel efficiency is improved or if aircraft performance is altered. The research process changed based on how the dependent variables reacted to the applied treatments. This method fits the design of this type of research as it is an experimental design that relies on cause and effect to determine how this longitudinal study will progress. Additionally, the method also improved the body of knowledge as it attempts to answer the questions that may be unanswered in the literature review or any specific source such as improving fuel efficiency with morphing wing structures. Concerning the subjects of study, the research focussed on fuel-efficient aircraft that can use morphing wing structures to be more fuel-efficient without compromising their performance. Testing was done on unmanned aerial vehicles (UAVs). UAVs are used in test studies such as this research and are commonly used as the first step before testing on larger aircraft such as commercial airliners as previously stated. This method attempted to answer the research question as it displayed the effectiveness of morphing structures in improving the carbon footprint of airplanes. The research question directly pertains to the topic of aerospace innovation and the method has the needed subjects that can lead to successful testing. This research used various instruments that are needed in testing and can emulate the designs of large-scale aircraft. In this study, the test model (UAV) had the morphing technologies applied and the results were recorded based on the reaction and adaptivity of the UAV to the treatments of the experiment. As mentioned before, UAVs are used in test studies such as mine which can be the first step before testing on commercial airliners or larger aircraft. In the beginning stages of testing, the researcher found it difficult to obtain the materials needed for proper testing which delayed the progress of the study. Such difficulties were faced by the researchers of the article Wind Tunnel Tests of 3D-Printed Variable Camber Morphing Wing when they were trying to test morphing structures using wind tunnels for a different type of aircraft. They placed special attention on the implementation of their procedures which resulted in their success and ridding of problems (Jia, 2022). In this case, the researcher used their experience in robotics and other engineering projects to solve the issues faced by the research. As far as the procedure, there is a long process that was followed as part of the longitudinal study which ensured the credibility and accuracy of the research. Firstly, data from various sources were combined and a conjecture was proposed about what the experiment would explain. Various tests needed to be conducted to answer the research question of how morphing structures could be implemented in aircraft to improve fuel efficiency without compromising performance. Ten trials were performed for each type of experiment and the averages were taken which ensures that the results are not a visualization of chance but are rather true numbers. Before the tests were conducted, the model UAV had to be constructed along with the morphing wing structures. The morphing structures were constructed using craft materials such as wooden skewers and a firm version of paper and styrofoam. The UAV was constructed using pre-fabricated parts which ensured that there was no bias involved. For the first test, to see whether morphing structures compromised the performance of the aircraft, the velocity of the aircraft was recorded by measuring the distance divided by time. This test was also to show whether performance was improved which could come as a byproduct of morphing wing structures. Each trial was completed in a set time of nine seconds. More importantly, the second test was to record the battery level of the aircraft to see how much battery the aircraft consumed within the same nine seconds. A lithium-ion battery, similar to those implemented in mobile phones and laptops, was used for this test as the UAV's only source of power. However, this battery is much weaker than those used in cell phones and laptops which resulted in fast depletion. Therefore, the time interval was kept short so that the battery level was not extinguished during testing. Since fuel is how much energy an aircraft uses during flight, battery level can be used in parallel to that to see how much energy the model UAV uses during this test. This displays how morphing structures impact the energy use of airplanes and will answer the research question of how fuel consumption can be reduced using morphing wing structures. This is the more significant test in this study since morphing structures would be pointless if they increased energy or fuel consumption. Both the tests were conducted with morphing structures equipped and without them to compare their effects.

RESULTS

After constructing the model aircraft or UAV (Unmanned Aerial Aircraft) for this research, modifications were made to the wings so that morphing actions could be performed. The morphing structures were applied to the wings so that they will directly and immediately affect flight performance and the results can be recorded from the moment it leaves the ground. The airplane was tested to travel the same amount of time each time and the distance was measured. The time traveled was restricted to nine seconds but the distance traveled was the focal point as it serves as the best way to compare the effect of morphing structures on the overall performance of the aircraft. It is also important to note that morphing structures do not provide any additional power to the UAV; they are just transformations of the wing structure to limit the effect of drag penalties caused by air resistance. Additionally, all data was used from ten trials for each type of experiment presented in the figures seen below. Those trials were then averaged to be displayed in a single figure and this process was repeated for all tests performed. With the morphing structures equipped, the aircraft was able to travel a further distance as shown in Figure 1.

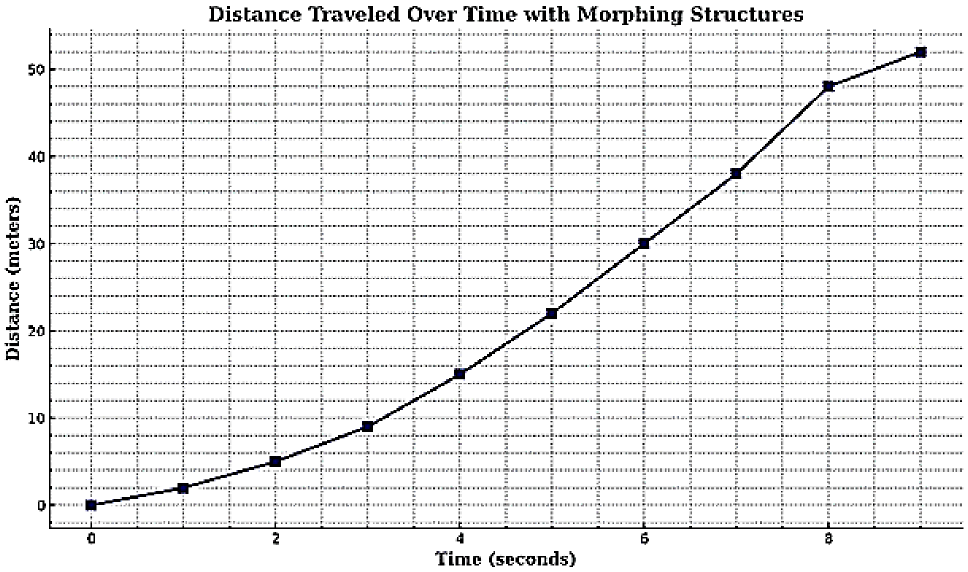

Figure 1. *Distance traveled with morphing structures.*

Figure 1 shows the relationship between distance and time when morphing structures are equipped and the rapid increase of distance traveled in the fixed 9 seconds.

For better understanding, a comparison can be made to the results when the plane did not have morphing structures as seen in Figure 2.

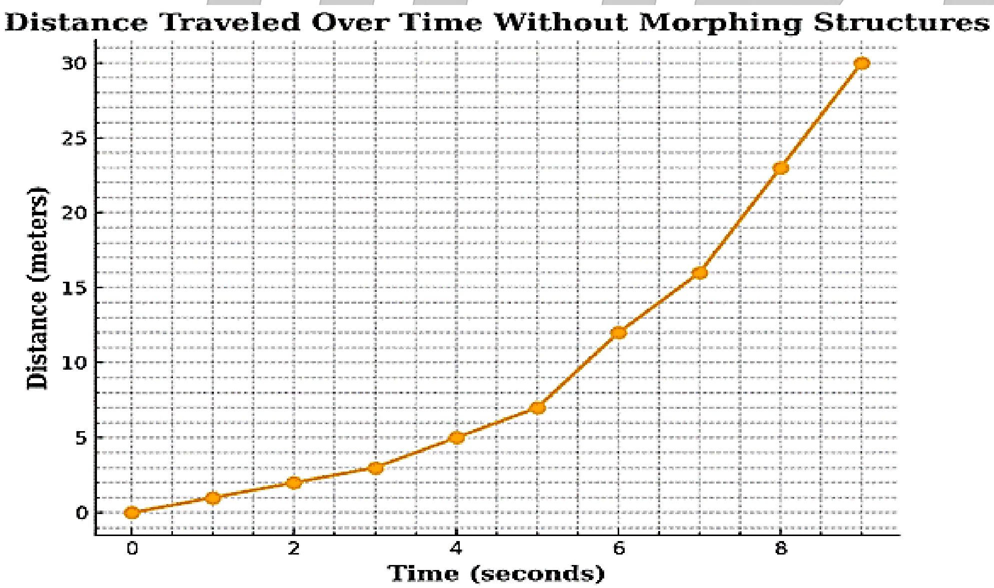

Figure 2. *Distance traveled without quipped morphing structures.*

In the same 9 seconds, the plane could only travel 25 meters, nearly 30 meters less than the distance shown in Figure 1 by the lane with morphing structures. The comparison shows a clear difference in the velocities of the aircraft with one being significantly higher. When looking at fuel efficiency, battery consumption was measured of the aircraft and the battery level of the electric aircraft used correlates with fuel level in an aircraft powered by engines. Figure 3 shows the battery level of the model UAV before morphing structures well applied and shows a constant decrease in the battery level.

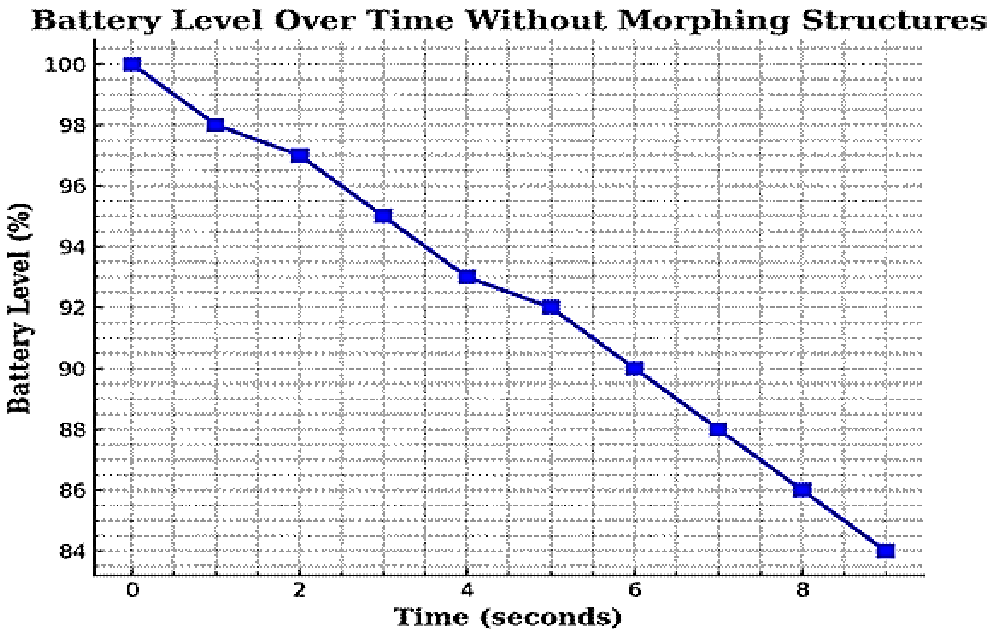

Figure 3. *Battery level without equipped morphing structures.*

The constant decrease of the battery is seen since there are no additions to the UAV that would affect its normal functioning. Morphing structures affect the aircraft's normal functioning so the battery level will change less invariably compared to when the UAV is normal. The wings were deformed from their original state using a separate technology that uses fluid dynamics which is not included in the normal functions of the plane so that the wings could be morphed during flight. The use of simple physics allowed the plane to take advantage of the wind conditions and fly with better performance even consuming less battery as shown in Figure 4.

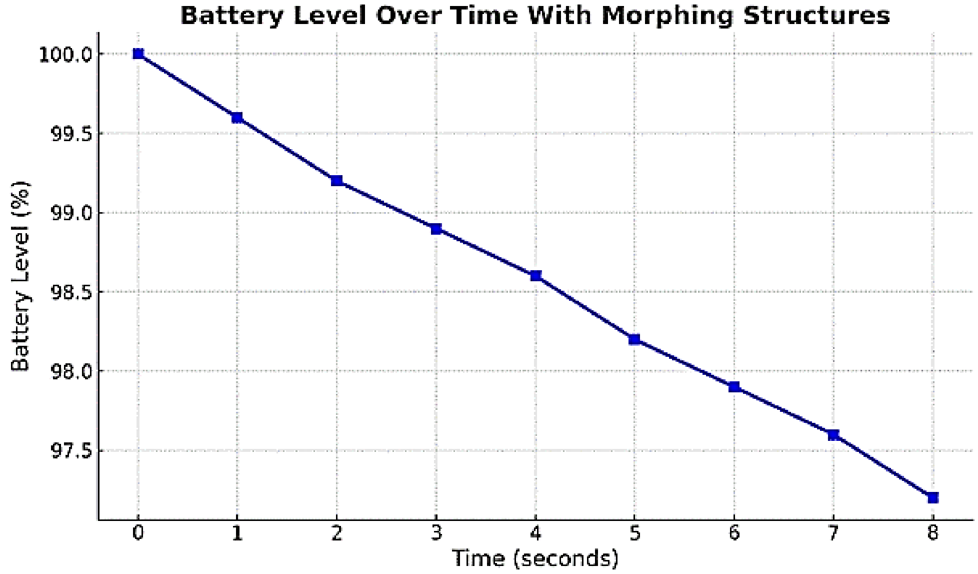

Figure 4. *Battery level with equipped morphing structures.*

The figure shows how there is a non-linear, but slowly reducing curve which ends with less battery percentage consumed than when there were no morphing structures equipped on the model UAV. The battery level on the model UAV can be correlated with the fuel level on a real aircraft since most of the energy for both types of aircraft is derived from the battery and fuel respectively. However, modern commercial aircraft also derive energy from more sophisticated sources such as alternators and generators which work with their engines.

Close attention was also paid to the performance of the model UAV's motors when the modifications were made. There have been many instances in the past where morphing structures or changes to the wings have caused unnecessary stress on the motors causing them to burn out or affect performance. One of the most important points in this study is to not compromise on performance when equipping the aircraft with morphing structures as that would affect the overall purpose of the study. After performing multiple trials and determining the averages shown in the figures, it was also determined that performance was not affected by the morphing structures as the motor was still able to push the aircraft to meet its top speed of 23 miles per hour without any difficulty.

ANALYSIS

The common factor between all experiment trials was the fixed flight time of nine seconds which is important because the maximum flight capacity was reached around a rapid four seconds of flight time since it was a battery-powered Unmanned Aerial Vehicle (UAV). When morphing structures were installed, the speed increased significantly over the ten seconds as it reached speeds around 5.5 meters per second and the UAV traveled almost sixty yards. When compared with the results when the model had morphing structures equipped, it is evident that the structures provide a boost in velocity as seen by the difference in distance traveled within the same time interval. It can be concluded that morphing wing structures do not compromise performance in any way. This aspect of the morphing structures also serves as an unexpected addition to the initial hypothesis as morphing structures had the purpose of not compromising overall flight performance but in this part of the experiment, they improved it. The trend that was noticed in all of the trials was that the morphing structures significantly improved the velocity of the plane and the distance traveled which showed a clear sign that the morphing structures are beneficial in this aspect. This experiment shows that with morphing structures, aircraft can travel further distances and at faster speeds when given a time interval which makes it economical for airlines. This increase in speed and distance traveled can be explained by how the wings with morphing structures adapt to the effects of wind resistance and other factors present at the time of flight. The morphed structures reduce the impact of air resistance and drag on the wings of the aircraft allowing the air to pass over the wing smoothly and not push against it like it would normally. Additionally, to address the significant concern of fuel efficiency, the battery level of the model was recorded which shows how the UAV uses its power or energy with and without morphing structures equipped. Without morphing structures present on the UAV, the battery level decreased at an approximately linear rate and reached slightly below the eighty-five percent mark after the time interval of nine seconds. On the other hand, when morphing structures were equipped, the battery level did not decrease significantly as it was around the ninety percent mark at the end of the time interval. The decrease was not perfectly linear since the functioning of the UAV is altered due to the morphing structures. The battery level of the UAV is an essential aspect of this research as it directly correlates to the fuel level of a full-scale aircraft. This correlation can be made since both a full-scale aircraft and the model used for this experiment derive their main source of energy from fuel and battery level respectively. However, modern commercial aircraft also derive energy from more sophisticated sources such as alternators and generators which work with their engines. In addition, it is important to note that the morphing structures are not a part of the aircraft model itself so the model in this experiment is not completely designed to adapt to morphing structures although modifications were made so that unnatural effects could be avoided during testing. Close attention was also paid to the performance of the model UAV's motors when the modifications were made. There have been many instances in the past where morphing structures or changes to the wings have caused unnecessary stress on the motors causing them to burn out or affect performance. Such attention is necessary since the research question aims to test morphing structures without compromising on performance and burned motors would not follow that protocol. Ten trials were also conducted for the battery-level experiments with morphing structures and without morphing structures to ensure that there was no chance involved and that the results remained accurate. After analysis of the trials, it was concluded that performance was greatly affected by the incorporation of morphing structures into the wing of the aircraft. However, the same conclusion cannot be made about the addition of morphing structures elsewhere on the model aircraft's fuselage as those incorporations were not tested in this research. Multiple limitations influenced the findings of this research such as the lack of equipment for better

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trials and the lack of wind tunnels as they were not possible to build in the time frame. Another limitation of these structures may be that they can be expensive in the initial stages of production as they will be new to the aviation industry. This will cause companies to be hesitant to invest in these structures which will delay the process of incorporating them into the industry. A weakness of the research method was that this research relied too heavily on the presence of wind tunnels when they were not incorporated into the study due to budget concerns. An alternative method for the testing environment aspect of the UAV could have been to consider indoor locations where the climate is controlled and perfectly constant for all testing runs. Additionally, there were external conditions such as varying wind conditions during the testing on the flight despite all tests being conducted simultaneously on the same day which slightly affected accuracy. In future tests, a neutral site such as a lab or indoor facility should be used so that such varying weather conditions can be avoided and test results can be even more representative of the equipped features. Furthermore, in future trials, a wind tunnel should also be used to ensure the physical state of the model UAV remains constant throughout trials and does not incur damages which was a possible occurrence in this experiment. However, none of the limitations significantly affect the validity of this research so they are not of high concern. The method used improved the legitimacy of the results by ensuring there was no bias involved and the results remained accurate with repeated trials. Additionally, assembling a model Unmanned Aerial Vehicle was very effective as it was easier to modify the components and incorporate morphing structures into the wings. This allowed the aircraft to still function properly contrary to what may have happened if the same was attempted on a pre-built model UAV. These results answered the research questions completely as they addressed how morphing structures can be used to improve fuel efficiency as seen by how they affected battery level and they also did so without compromising the performance of the UAV. Rather, they improved the performance of the UAV which was not expected on a model of this scale. However, since the model was at a small-scale level and the morphing structures were only added to the wings, there can be further research to be done to determine the legitimacy and further improvements that can be done with morphing structures. When comparing these results to other studies such as Wind Tunnel Tests of 3D-Printed Variable Camber Morphing Wing, which also research morphing structures, the results are similar regarding velocity. This shows how morphing structures can be applied to the wings to improve the environmental footprint of aircraft and can also improve the overall performance of the flight which will save money for airlines in the future. Additionally, the implementation of these structures will eventually make airfare cheaper for the general public as fuel costs for airlines will be reduced, leaving them with fewer expenses and more flexibility for airfare. This study complements Jia's study and serves as an addition to it when looking at morphing structures.

CONCLUSION

In this paper, a model of Unmanned Aerial Aircraft (UAV) was used to test the effects of morphing wing structures on fuel efficiency without compromising flight performance. The flight was constructed using cardboard and strong papers which ensured its durability during flight to avoid lost data. The quantitative data recorded during flight comparing flight performance with morphing structures and without morphing structures was determined by the flight time and distance traveled in that time. Furthermore, the possibility of power input difference or the variation of power used depending on equipped features was avoided by ensuring a fixed amount of battery power was provided to the aircraft using all test trials. The study's main contributions are: This morphing wing can be implemented in larger-scale aircraft to improve fuel efficiency with a low chance of reduced performance after testing is completed; the morphing wing can also improve flight performance depending on external factors such as drag due to wind resistance. These serve as implications of this study for the aerospace industry and can also serve as a major breakthrough when further testing is conducted to ensure its validity. In the study Wind Tunnel Tests of 3D-Printed Variable Camber Morphing Wing, the researchers had a large budget and ample resources to conduct their experiment on the flexibility of morphing wings which allowed them to have more accurate and legitimate results. Such resources would have allowed this research to be completed with more advanced instruments. Nevertheless, this paper serves as the initial step in using morphing wing structures to improve fuel efficiency and protect the environment. Overall, the aerospace industry can benefit from findings as such along with other studies that have been conducted involving this topic which enhance other parts of aircraft flight. The aerospace industry can expect to see morphing structures in production lines in the future and will see plenty of benefits from them despite early challenges.

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