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"Breaking the Friction: Active Flow Control Tackling the Challenge in Aircraft Fuel Consumption and A Brief Outlook to the Future of Aerospace Applications"

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ABSTRACT

This paper gives an introduction to the principles behind Active Flow Control (AFC) and its potential to reduce aerodynamic drag followed by the latest experimental data gathered by our in-house setup. An AFC system consists of a network of sensors and actuators whose role is to reduce aerodynamic drag through local surface modulation. A thorough analysis and a discussion of the results obtained from experiments which simulate the use of an AFC system through the modification of the surface of several material samples exposed to airflows (aimed at various diverging angles towards the sample surface) will be presented. Our experiments involved the use of a MARK-10 Series M3-5 force meter which measured the load experienced by the normal and modified surface of Titanium, Aluminum, Carbon Fiber, Hardboard, and Cardboard materials. Additionally, we will examine the effects the materials' distinct thermal, electrical, and mechanical properties relevant for their suitability to certain applications. The conclusion will include observations on recent development in aerospace applications from composites to avionics, to biomimicry, as well as future research interest in AFC and other areas of increasing importance in the aerospace field.

Keywords: Aerospace Technology, Active Flow Control

1. Introduction

As we demonstrated in our previous works[1], the aerospace industry has been a leader in technology development and innovation. From designing the engines of planes that meet commercial aviation's rising needs to launching rockets and satellites to developing the structures of military planes, scientist and engineers have been at the vanguard of the research and development of the aerospace technologies. Still, the industry has an ever increasing demand to deliver higher quality products that will result in greater efficiency. It is by continuing to innovate that we will create the materials to build the next generation of faster, more efficient air and space vehicles, as well as the avionics systems for navigation and the propulsion needed to fly them. Our hypothesis is to observe the localization of the air flow due to the surface modification into an aerodynamic structure thus, resulting into a reduction in aerodynamic drag. To support this hypothesis, a series of preliminary experiments which established the potential merits of an AFC system were designed and performed as presented in our earlier work[1]. Those experiments verified that a material's physical properties play a significant role in the performance of any given system and their surfaces can experience higher loads for stronger, more turbulent air flows. The results presented at the NCUR 2017 conference were generated from a new set of experiments, which sustained some of the preliminary findings, and provide more technical knowledge in AFC systems.

2. Background

Aerodynamic drag (turbulence) is a leading cause of increased aircraft fuel consumption. The drag is mainly composed of skin friction which results from the boundary layer separation during flights; the separation of this laminar flow from the surface disturbs the boundary layer by creating a low pressure region which increases the turbulent flow (drag). Drag reduction can be achieved by an AFC system relying on active surface modulation though the use of active flipperons which will be responsible for reduction of air drag and, in turn, fuel consumption. In other words, the system will consist of arrays of sensors and actuators (e.g. flipperons). The sensors will track physical quantities such as pressure and vibrations which will activate the actuators in order to compensate for the disturbance and, as a result, reduce the air drag. For a more in depth discussion of the effects of aerodynamic drag in fuel consumption as well as ongoing research on different types of AFC technologies, in particular Cyber-Physical Systems (CPS) for AFC, the reader is directed to reference[2]. Although it is not a new concept, the AFC system prototype developed in 2008 by James H. Mabe from Boeing of the Langley Research Center enabled the evaluation of AFC benefits for aircraft. The integration of different elements into a complete, controllable prototype is an example of how existing technologies can be further improved with new designs. The underlying principle consists of using flight-control surfaces known as flipperons to control airflows and, thus, increase aircraft performance[3].

3. Experimental Section

This set of experiments had two main purposes: 1) to improve both accuracy and precision with the use of a new force meter device, the MARK-10 Series M3-5 (see figure 1 below), which is a much better, properly calibrated instrument than the one previously employed and 2) to increase the material samples tested by including Titanium, Aluminum, and Carbon Fiber in addition to the Cardboard and Hardboard samples tested in the preliminary experiments (see figure 2 below). All material samples tested were standardized 6x6 inch square in shape.

Figure 1: Mark-10 Series M3-5 force meter

Figure 2: Materials samples tested

The end purpose of the new experiment is to demonstrate once more that when a surface undergoes a certain modification and localizes the air flow within the surface, the surface becomes more aerodynamic and, as a result, it experiences a reduction in aerodynamic drag when exposed to a particular fluid flow or combination of flows. Ten experiments were performed in all; two experiments were performed for each sample—the first experiment recorded the load experienced by the sample without modification for a total of five trials and the second recorded the load after the sample had been modified with bubble wrap (see figure 3 below) for five other trials. For each experiment, the sample was exposed separately to two different air flows as well as a combination of the flows.

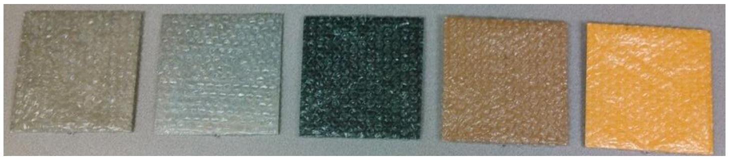

Figure 3: Modified material samples

Below, figure 4, is a picture showing the top view of the equipment layout and setup used to conduct the experiments.

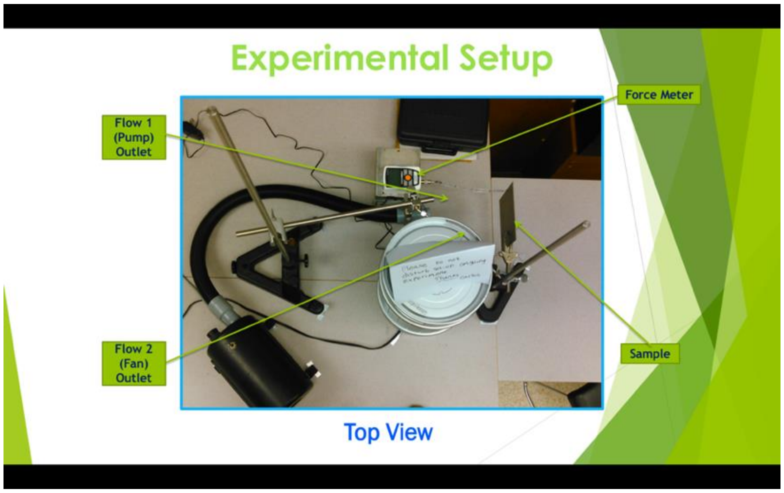

Figure 4: Top view-experimental setup and equipment layout

All physical parameters, except the surface modification, are kept constant for all samples. The experiments demonstrated a reduction in air drag by modifying the coefficient of friction of each surface. The mathematical relationship between the drag coefficients and surface parameters is

$$c_d = \frac{2D}{pv^2A} \quad (1)$$

c_d=Drag Coefficient
D=Drag Force
ρ=Mass Density of Fluid
v=Velocity of Air
A=Surface Area

4. Results and Discussion

4.1 Experiments 1-A and 2-A

In *experiment 1-A*, the titanium sample was exposed to an air flow generated by a pump (hereafter named *Flow 1*), the air flow generated by a fan (hereafter named *Flow 2*), and the combination of these two air flows. The data gathered for each trial is shown in the following Table 1.

Table 1: Load values experienced by titanium for the different flow configurations

	Flow 1	**Flow 2**	**Combined Flow 1 & 2**
	Load (KgF)	**Load (KgF)**	**Load (KgF)**
Trial	**Value**	**Value**	**Value**
1	0.034	0.000	0.046
2	0.034	0.000	0.046
3	0.036	0.000	0.048
4	0.036	0.000	0.048
5	0.038	0.000	0.050

As we can see from Table 1, above, results for titanium are consistent with previous experimental trends. The sample experienced higher loads when exposed to a combination of flows. Even with the new force meter, *Flow 2* alone was not large enough to register a value. Still, we can see that when a random air flow appears, no matter how negligible it might seem, it will increase the turbulence of a surface already subjected to a particular load.

For *experiment 2-A*, the titanium sample was modified using bubble wrap. Aside from the modification, the same configuration as for *experiment 1-A* was used. The results are summarized in Table 2 below.

Table 2: Load values experienced by modified titanium for the different flow configurations

	Flow 1	**Flow 2**	**Combined Flow 1 & 2**
	Load (KgF)	**Load (KgF)**	**Load (KgF)**
Trial	**Value**	**Value**	**Value**
1	0.010	0.000	0.024
2	0.012	0.000	0.026
3	0.012	0.000	0.026
4	0.014	0.000	0.026
5	0.016	0.000	0.028

Once more in *experiment 2-A*, we can observe the same correlation seen in previous experiments between *Flow 1* and the combination of *Flow 1 and 2*. The difference, nonetheless, can be seen in the lower loads experienced by the modified titanium surface providing indisputable evidence of the benefits of a potential AFC system.

Figure 5, below, is a graphical representation of the results from *experiments 1-A and 2-A*. As we can see, the regular titanium surface exposed to the combinations of flows experienced the higher load values, followed by the regular surface exposed to *Flow 1* only. The modified titanium surface experienced lower loads for both flow configurations with the *Flow 1* only configuration being the lowest.

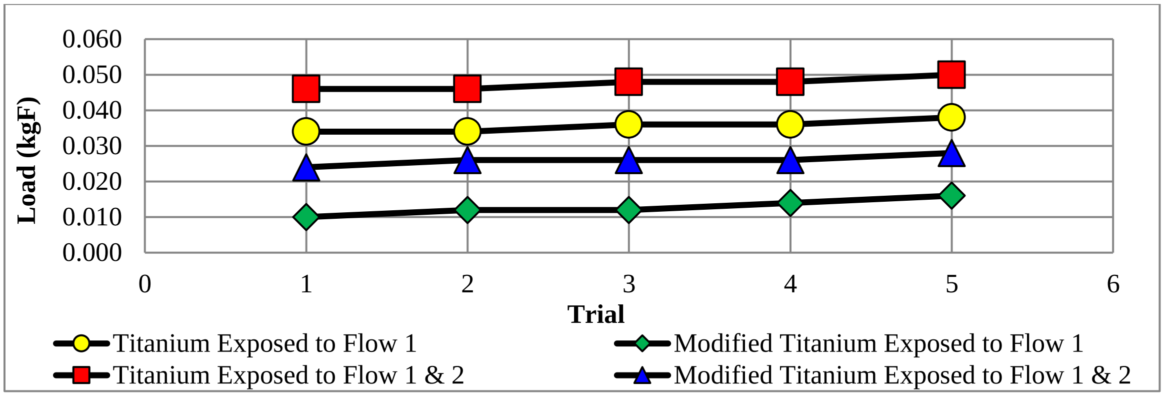

Figure 5: Summary of experimental results for titanium and modified titanium surface

4.2 Experiments 1-B and 2-B

E*xperiment 1-B* followed the same procedure and setup as *experiment 1-A*, but for the aluminum sample. The data acquired is presented in the following Table 3.

Table 3: Load values experienced by aluminum for the different flow configurations

	Flow 1	**Flow 2**	**Combined Flow 1 & 2**
	Load (KgF)	**Load (KgF)**	**Load (KgF)**
Trial	**Value**	**Value**	**Value**
1	0.022	0.000	0.036
2	0.022	0.000	0.038
3	0.022	0.000	0.040
4	0.024	0.000	0.040
5	0.026	0.000	0.040

The trend seen in Table 3, above, for aluminum is much like the one shown in Table 1 for titanium. The aluminum sample, however, experienced loads about 30% times higher for each flow configuration.

For *experiment 2-B*, the setup and procedure were the same as in *experiment 1-A*, but the readings were for the bubble wrap modified aluminum sample. Table 4, below, gives the specific values for each flow configuration.

Table 4: Load values experienced by modified aluminum for the different flow configurations

	Flow 1	**Flow 2**	**Combined Flow 1 & 2**
	Load (KgF)	**Load (KgF)**	**Load (KgF)**
Trial	**Value**	**Value**	**Value**
1	0.014	0.000	0.022
2	0.016	0.000	0.024
3	0.016	0.000	0.026
4	0.016	0.000	0.028
5	0.016	0.000	0.028

From Table 4, we can clearly see the lower load values experienced by the modified aluminum sample when compared to the loads experienced by the regular aluminum surface sample given in Table 3.

An overview of all results is given in figure 6 where we can see that the regular aluminum surface exposed to the combination of *Flow 1 and 2* had the highest load values. Then, a clear reduction for the modified aluminum surface, when exposed to the combination of flows, tailed by the regular surface exposed to *Flow 1* only and finally the modified surface exposed as well only to *Flow 1*.

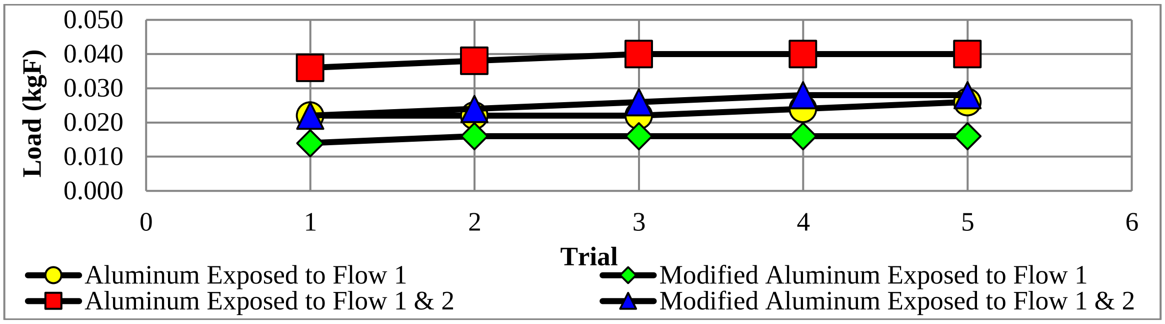

Figure 6: Summary of experimental results for aluminum and modified aluminum surface

4.3 Experiments 1-C and 2-C

In *experiment 1-C*, the carbon fiber sample was tested using the same configuration used in *experiment 1-A*. The data acquired is compiled below in Table 5.

Table 5: Load values experienced by carbon fiber for the different flow configurations

	Flow 1	**Flow 2**	**Combined Flow 1 & 2**
	Load (KgF)	**Load (KgF)**	**Load (KgF)**
Trial	**Value**	**Value**	**Value**
1	0.024	0.000	0.034
2	0.026	0.000	0.036
3	0.028	0.000	0.038
4	0.028	0.000	0.036
5	0.028	0.000	0.038

The results in Table 5 demonstrate a performance for carbon fiber in line with that of the previous materials tested. The sample experienced higher loads when exposed to *Flow 1 and 2* combined, lower loads for *Flow 1* only, and a negligible load for *Flow 2* alone.

Experiment 2-C was for the modified carbon fiber sample. The same configuration as for *experiment 1-A* was used. The obtained values can be seen in Table 6 which follows.

Table 6: Load values experienced by modified carbon fiber for the different flow configurations

	Flow 1	**Flow 2**	**Combined Flow 1 & 2**
	Load (KgF)	**Load (KgF)**	**Load (KgF)**
Trial	**Value**	**Value**	**Value**
1	0.006	0.000	0.010
2	0.006	0.000	0.012
3	0.008	0.000	0.014
4	0.008	0.000	0.014
5	0.008	0.000	0.016

In *experiment 2-C*, we observe around a 60% reduction of the load experienced by the modified carbon fiber surface when compared to the loads of the regular surface. As expected, the load experienced by the surface for *Flow 1* only is much lower than the combined flows.

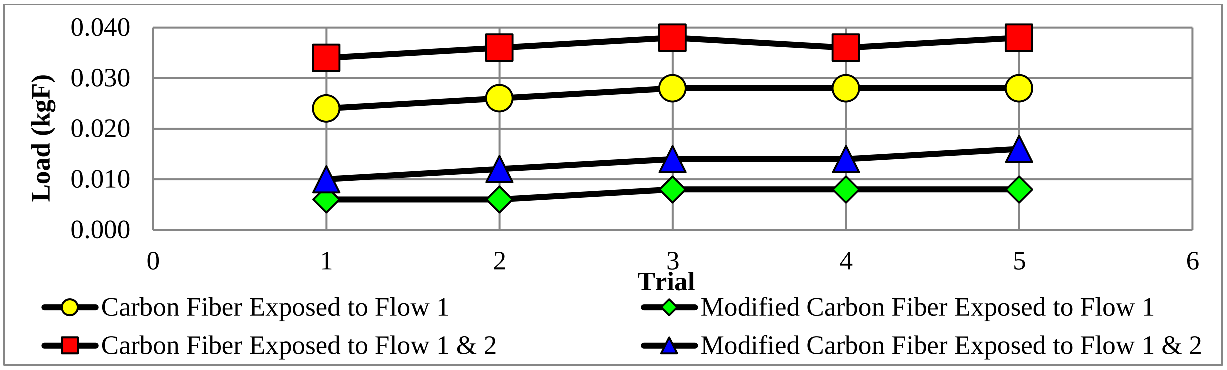

Figure 7: Summary of experimental results for carbon fiber and modified carbon fiber surface

The graphical representation of the results for *experiments 1-C and 2-C* can be seen in figure 7; the regular carbon fiber surface exposed to the combinations of *Flows 1 and 2* experienced the highest load values followed by the regular surface exposed to *Flow 1* only. We can see a significant reduction in the load experienced by the modified surface when exposed to *Flows 1 and 2* and, finally, the lowest loads were experienced by the modified surface exposed to *Flow 1* only.

4.4 Experiments 1-D and 2-D

For *experiment 1-D*, the data for the regular hardboard sample was gathered using the same methodology as for experiment 1-A; the results are provided in Table 7 below.

Table 7: Load values experienced by hardboard for the different flow configurations

	Flow 1	**Flow 2**	**Combined Flow 1 & 2**
	Load (KgF)	**Load (KgF)**	**Load (KgF)**
Trial	**Value**	**Value**	**Value**
1	0.006	0.000	0.012
2	0.006	0.000	0.012
3	0.006	0.000	0.012
4	0.006	0.000	0.012
5	0.006	0.000	0.012

In Table 7, we observe much lower overall values, but the results still follow the same trend we have seen thus far with the sample experiencing higher loads for the combination of *Flow 1 and 2* and lower loads for *Flow 1* alone.
Then, for *experiment 2-D*, the hardboard sample was modified using bubble wrap. Except for this modification, the setup was the same as for *experiment 1-A* and the values obtained are reported in Table 8.

Table 8: Load values experienced by modified hardboard for the different flow configurations

	Flow 1	**Flow 2**	**Combined Flow 1 & 2**
	Load (KgF)	**Load (KgF)**	**Load (KgF)**
Trial	**Value**	**Value**	**Value**
1	0.002	0.000	0.006
2	0.002	0.000	0.008
3	0.002	0.000	0.008
4	0.004	0.000	0.008
5	0.004	0.000	0.010

As expected, the loads were lower for the modified hardboard surface, albeit to a less extent, than for the other material sample surfaces. *Experiment 2-D* is no exception and we can see higher and lower loads respectively, for the combined flows and for *Flow 1* only.

A summary of the results can be seen in figure 8, where the highest loads are recorded for the regular hardboard surface exposed to the combination of *Flow 1 and 2* followed by a small reduction in the load values obtained for the modified surface exposed as well to the combined flows. Then, we see very stable values for the regular surface exposed to *Flow 1* tailed by the expected reduction in load values for the modified surface also exposed to *Flow 1* only.

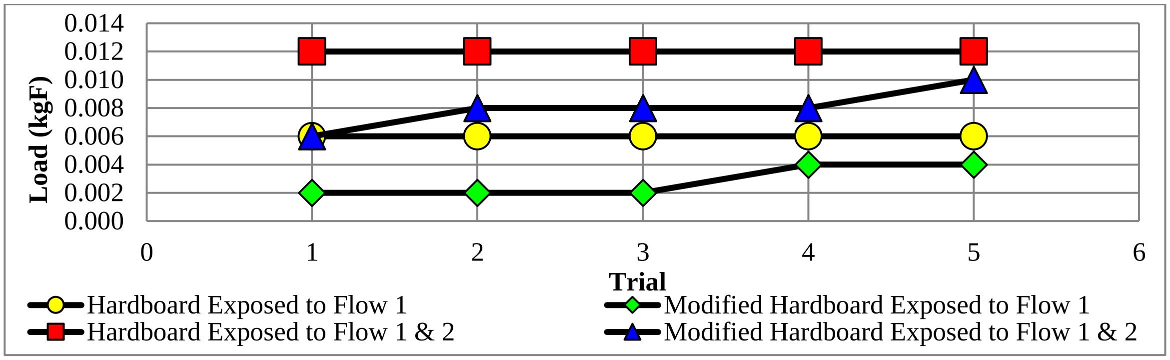

Figure 8: Summary of experimental results for hardboard and modified hardboard surface

4.5 Experiments 1-E and 2-E

The results obtained for the cardboard sample in *experiment 1-E* can be seen in Table 9 below; the same procedure as for *experiment 1-A* was applied.

Table 9: Load values experienced by cardboard for the different flow configurations

	Flow 1	**Flow 2**	**Combined Flow 1 & 2**
	Load (KgF)	**Load (KgF)**	**Load (KgF)**
Trial	**Value**	**Value**	**Value**
1	0.040	0.000	0.046
2	0.040	0.000	0.046
3	0.040	0.000	0.046
4	0.040	0.000	0.048
5	0.040	0.000	0.048

In Table 9, we can see higher load values for the combined flows and slightly smaller values when the surface was exposed to *Flow 1* only. The trend observed remains constant with that from previous experiments.

For e*xperiment 2-E* the cardboard sample was modified using bubble wrap. The experimental procedure was the same as for *experiment 1-A* and the data compiled is given in Table 10.

Table 10: Load values experienced by modified cardboard for the different flow configurations

	Flow 1	Flow 2	Combined Flow 1 & 2
	Load (KgF)	Load (KgF)	Load (KgF)
Trial	Value	Value	Value
1	0.032	0.000	0.040
2	0.034	0.000	0.042
3	0.034	0.000	0.042
4	0.034	0.000	0.044
5	0.036	0.000	0.044

The modified cardboard sample had the smallest reduction between the regular and modified surface of all samples tested. Nevertheless, the reduction is still evident and follows the usual trend between *Flow 1* and the combination of *Flow 1 and 2* seen in other experiments.

Finally, all the results for *experiments 1-E and 2-E* can be seen in figure 9 below. The highest load values are again for the regular surface exposed to the combination of *Flows 1 and 2* followed by the reduction for the modified surface exposed to the combined flows. Then, we see stable values for the regular cardboard surface exposed to *Flow 1* alone and the lowest values are for the modified surface exposed only to *Flow 1*.

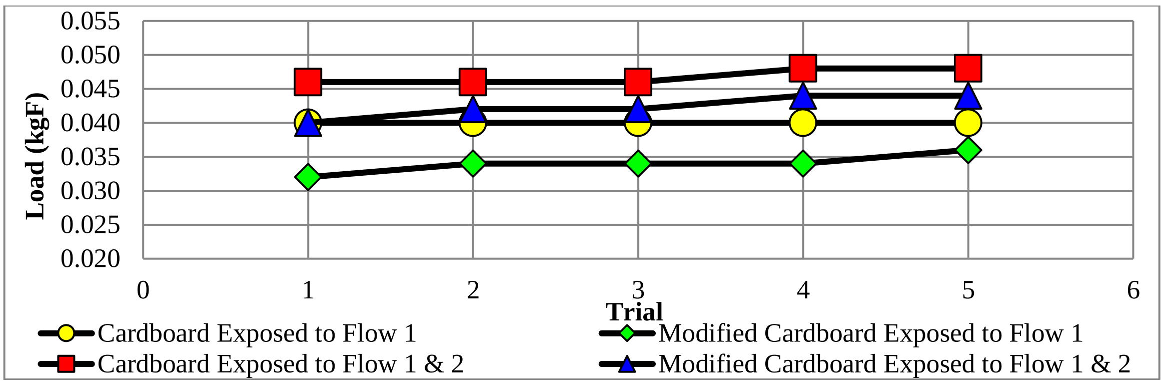

Figure 9: Summary of experimental results for cardboard and modified cardboard surface

It is critical to understand how big of a difference the flow control system introduced by modifying the surfaces made in reducing the aerodynamic drag or turbulence. As far as aerospace applications are concerned, the experiment supports the claim that modifying an aircraft's surface with some kind of flow control system will reduce the aerodynamic drag. Ultimately, we observed that the modified surfaces for each sample experienced lower loads than the non-modified surfaces regardless of whether they were exposed to *Flow 1* alone or the combination of *Flow 1 and 2*. Additionally, while the flow control system is effective for all samples, its effectiveness depends on the different materials' mechanical and thermo-electrical properties (e.g. carbon fiber has some unique properties which make it better suited to handle the air flows than aluminum).

5. Conclusion

With an ever increasing demand in the use of air transportation, emphasis has been placed in reducing the cost and increasing the efficiency of air travel. Fuel costs seem to be the single most influential factor driving up the price of air transportation. Thus, one can conclude that design improvements in aircraft resulting in reduced fuel consumption will improve the overall efficiency of air travel. One such way to reduce the aerodynamic drag or turbulence is to modify surfaces exposed to the air flow so as to make them more aerodynamic. This can be accomplished through the use of an AFC system. While the concept of using particular shapes and or flipper-like structures to control flows is not new, the AFC system detailed in the background section is yet to be developed due to design challenges caused by the small length and the time scales which are characteristic for turbulent flows. From our study, we can determine that a modified surface creates a more efficient air flow which reduces aerodynamic drag; this finding is important and beneficial in order to achieve better fuel consumption efficiency in the aerospace industry. Finally, our experimental results demonstrate that composite materials possessing the adequate balance between strength, lightweight, and elasticity can efficiently reduce aerodynamic drag. Ultimately, the AFC systems will consist of a network of sensors and actuators integrated into light smart materials such as lightweight piezoelectric materials; this network could then be integrated with flexible materials such as optical fibers which in turn could be embedded into the aircraft surface.

Future AFC research remains promising, however, with the goal of discovering new ways to improve overall efficiency in different aerospace applications, several areas of interest were investigated. For example, Solar energy harvesting devices consisting of organic photovoltaic (PV) fibers[4] have the potential of being integrated into the composites generating aerospace structures. Then, if we also take advantage of advances in composite materials[5] to build aircrafts, we would increase even more the total efficiency of an air vehicle. Lighter, sturdier, and more heat resistant composite materials must be used in the construction of aircraft structures as well as the parts in the engines that propel them. In the field of avionics, research is critical in three particular categories which are essential to the development of more efficient onboard avionics system: 1) design considerations for Integrated Modular Avionics (IMA) platforms[6], 2) system adaptability to different types of air and space vehicles, and 3) products used in the construction of the system. Finally, the realization that the exiting field of biomimicry could be brought into aerospace applications came after studies of the microscopic structure of a whale's skin which gives to whales the ability to move through the water with almost no friction and more efficiently than other organisms. Biomimicry is the name given to the strategy of looking to different life forms or processes in nature and applying them as a logical solution to different design problems. Biomimicry is a proven method that has been used to solve design challenges on multiple occasions from things such as bullet trains to radio frequency identification technologies. An article published in the website of the American Society of Mechanical Engineers[7] beautifully describes biomimicry and provides examples of its applications. The article explains how the chief engineer for Japan's 200-mph Bullet Train modeled the front of the train after the beak of a kingfisher. Another example indicates how the fundamental wing structure of the Blue Morpho butterfly reflects light with very high levels of efficiency and, as a result, provided inspiration for radio frequency identification technology. In short, the article demonstrates that nature is full of incredible design solutions for common and uncommon engineering problems. One such way to use biomimicry to enhance the structure and processes of aerospace systems could be to look at biological system for inspiration in AFC technologies. Nature is full of marvels which can certainly provide solutions to the most simple or complex engineering problems. Biomimicry is a truly exciting field which can be used for innovation in aerospace applications; organisms such as birds in the air and fishes in the sea could, indeed, hold the key to improve aerodynamic performance[1].

6. Acknowledgments

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