Using Piezoelectric Materials on the Surface of Air Foils to Generate Voltage

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The piezoelectric effect is a property that allows certain materials to produce a voltage in response to a mechanical stress and vice-versa. Some well-known piezoelectric substances include quartz and Rochelle salt; these materials, when stricken, can generate a spark. Recent efforts to uncover sources of renewable energy have led to in-depth research of piezoelectric materials, which can act as voltage generators if exposed to constant mechanical stress (i.e. vibrations). The goal of this experiment was to investigate whether piezoelectricity would be able to provide a significant source of voltage to supplement a UAV or any aircraft.

To create a piezoelectric energy harvesting circuit, a bridge rectifier and capacitor were wired to the piezoelectric materials. This configuration was attached to the wings of a plane (either a large air foil or a Cessna 172) in an attempt to produce a voltage in response to vibrations created by turbulence, the airfoils, or the motor. In the end, the macro-fiber composites were able to generate a measurable, if not slightly minuscule voltage, on the large airfoil model. This could potentially serve as supplemental energy for extended flights on UAVs if the vibrational energies were increased via greater speed and turbulence. Additionally, if fixed to the wings of a full-sized aircraft, the energy produced could provide the plane with a supplemental energy source for radio, navigation, and lighting components.
INTRODUCTION

Piezoelectricity is the charge that is generated within certain naturally-occurring materials when force is applied. Some substances can also be turned into piezoelectric entities when an electric field is applied to the material (Fig. 1).

![Diagram](image1.png)

**Fig. 1:** Application of pressure, impact, or acoustic wave results in voltage output; and vice versa (Digital Image)

This becomes possible when localized dipoles become oriented in the same direction (Sodano, et al.). Dipoles are molecules with an unequal distribution of charge. This distribution is created by the electronegativity (ability to attract electrons) differences between the individual atoms that make up each molecule in the material (Fig. 2). In the case of piezoelectric materials, when the material experiences mechanical stress, it can produce a measurable voltage due to the unequal charge distribution. Conversely, the reverse piezoelectric effect can also be observed: a piezoelectric material that experiences a voltage will deform mechanically.

![Diagram](image2.png)

**Fig. 2:** A: molecules within material have random dipoles. B: molecules are all polarized in the same direction (Safari et al.)

Piezoelectric materials are often used as a way to measure pressure and force in sensor systems or as actuators. However, some researchers have sought to harvest piezoelectricity from vibrations such as those produced by moving vehicles. For example, one group in Israel was able to utilize the piezoelectric effect to generate four-hundred kilowatts of power from a one kilometer strip of highway by harvesting energy from the vibrations of passing automobiles (“The Future of Piezoelectric Generators”). Other researchers have been looking to piezoelectric materials to provide an internal generator for self-sustaining microelectromechanical systems (MEMS) and other devices which cannot be charged after deployment (Stewart, et al.).

Unmanned aerial vehicles (UAV) could benefit from on-board piezoelectric generators because they would provide supplemental power without
significantly increasing the load on the plane. The United States military is currently investigating the use of piezoelectric materials in its UAVs and mini-UAVs to extend the flight time of reconnaissance missions (Maillard, et al.). However, the issue of limited flight time applies not only to the military environment, but also to the commercial and private aviation sectors.

Thus, the goal of this experiment was to utilize the principle of embedding piezoelectric materials in the wings of an aircraft to test whether it could be applied to a more versatile range of aircraft such as remote control (RC) planes, small recreational planes, or even commercial jets. Because of the decreased load on the electrical system from the battery, aircraft could potentially use less fuel, fly with lighter loads, and become less expensive to operate.

To determine the maximum voltage that could be generated, it was necessary to find the optimal location to place the piezoelectric material. This arrangement was determined for both a large wing model and a full-sized Cessna 172. Through the use of a single moving wing model: it was ensured that wind, not motor vibrations and other unwanted factors, were the sole generators of voltage so that it could be determined whether or not wind and turbulence played a factor in the generation of voltage.

**MATERIALS AND METHODS**

*Bench Tests and Circuit Design*

Several circuit designs were tested on a breadboard to determine the ideal configuration of the energy harvesting circuit. Once the optimal circuit design was found, the circuit elements were removed from the breadboard and soldered together. The piezoelectric material was also soldered to the alligator clips to prevent disconnection. The final circuit consisted of two M-8514-P1 macro fiber composites from Smart Material connected in parallel to a silicon bridge rectifier circuit using alligator clips to allow for easier rearrangement of the macro fiber composites (Fig. 3).

*Fig. 3: The piezoelectric energy harvesting circuit*
The purpose of the rectifier was to convert alternating current (generated by the stressed piezoelectric material) into direct current by a series of diodes so that the voltage can be stored and measured. The rectifier then led to a .22 microfarad polyester-film capacitor, which stores the voltage in a reservoir. The voltage accumulated during experimentation by the capacitor was measured using a voltmeter, with values being recorded manually every five seconds.

Choosing a Capacitor

The specific capacitor utilized was a polyester film capacitor. This capacitor has a low leakage current in comparison to its small size making it the optimal choice for harvesting small amounts of energy (Features & Applications). Its low time constant also makes it more sensitive to changes in voltage, which allowed for more accurate monitoring during experimentation. The capacitor can store voltage temporarily, but cannot hold power so voltage readings needed to be taken continuously by the data logger. A larger capacitor could have stored more voltage in total, but would not have read acute changes over time.

Piezoelectric Material

The piezoelectric component utilized for this experiment was an M-8514 P1 macro fiber composite (MFC) piezoelectric as opposed to the P2 macro fiber composite (which is designed for energy harvesting) mainly due to budget constraints. Macro fiber composites are “characterized by their flexibility on large deformation, which enables them to harvest energy from ambient vibration sources with little brittle risk and long lifespan.” (Yang et al.). A P1 type of MFC patch was also used in the project Energy Harvesting for Unmanned Aerial Vehicles (Anton). Additionally, the P1 type MFCs are typically very sensitive strain sensors, unlike the larger P2 and P3 type MFCs, which are mostly used for energy harvesting. This makes the P1 type better suited to sense small amounts of force (Daue et al.), which is why it was appropriate for this small-scale experiment. Sensitive material makes for easy, more accurate reading of data.

Experimental Setup for Large Airfoil

It was hypothesized that at faster flight speeds, the vibrations of the wing would be greater than those produced at lower speeds, thus yielding a higher voltage. Being that larger planes normally travel faster than smaller planes (due to larger, more powerful engines), using a larger airfoil to test piezoelectric voltage generation was considered to be more accurate to real life application. It is also important to note that in a small RC plane, a majority of the mechanical vibration is derived from the engine. It is possible that the larger wing size will experience more mechanical stress from the wind in comparison to the vibrational energy derived from the engine.

The wings of a large RC plane (wingspan: 178.5 cm) were used to isolate the variable of the vibrations of the material due to the air. In most UAVs or RC planes, the vibrations from the motor provide the majority of the vibrations for the MFC. To eliminate this uncertainty, a stationary wing was used. The piezoelectric components were affixed to the wing using electrical tape in multiple configurations with different amounts of MFC movement allowable.

To simulate flight situations, the wing was positioned outside the passenger window of a campus transport van, which drove at an average speed of 6.7 meters per second (15 miles per hour) (Fig. 4). It was assumed that the wind speed would replicate a flight situation.
The same circuitry was used in all trials. The piezoelectric materials were connected to the rest of the circuit through alligator clips, rather than a single wire, to have the option to change the distance between the MFC and the circuit. Additionally, the circuit was attached to the wing using electrical tape (Fig. 5). The voltage was measured manually at time intervals of 5 seconds using a voltmeter.

**Fig. 4:** Large wing outside of van window

**Fig. 5:** MFC Configuration on Large Airfoil (Note: The data logger shown was replaced by a voltmeter for testing.)
**Experimental Setup for Cessna 172**

Similar to the large RC wing configuration, the MFC was attached to the Cessna 172 wing with electrical tape in two different locations - the leading edge of the wing near the fuselage (body of the airplane) and on an open window, allowing the MFC to move more freely (Fig. 6). The circuit and data logger were inside the plane, connected by multiple alligator clips and extra wiring. The plane was then taxied at approximately 11.2 meters per second (25 miles per hour) while data was recorded (1 sample/5 s).

![Fig. 6: Cessna experimental configuration 1 - leading edge of wing (left); Cessna experimental configuration 2 - inside of open cockpit window](image)

**RESULTS**

In the first recorded trial (Fig. 7), the MFCs were attached to the leading edge of the airfoil, with the van driving at an average speed of approximately 6.7 meters per second. The MFCs were only taped at one end of each strip to allow for more freedom of movement. The voltage reached a peak of 128.8 mV and a low of 7 mV, but typically read between 10 and 40 mV.

![MFC on wing (taped on one end)](image)

**Fig. 7:**
*MFCs taped on the leading edge of the airfoil, at only one end of each strip (1 sample/5 sec)*
The second recorded trial (Fig. 8) placed the MFCs on the leading edge of the air foil again, but taped more securely. The van drove at a speed between 4.5 and 6.7 meters per second. The voltage reached a peak of 128.9 mV and a low of 2.1 mV.

![MFC on wing (taped on both ends)](image)

**Fig. 8:**
*MFCs taped on the leading edge of the air foil, at both ends of each strip (1 sample/ 5 sec)*

The third recorded trial (Fig. 9) involved taping both sides of the MFC to the underside of the wing closest to the attachment site. This trial maintained consistent voltage charge and discharge relative to the other trials. However, the maximum voltage produced (63.1 mV) was far less than the maximum voltage output of the other trials. The minimum voltage output of this trial was 8.5 mV. During this test, the effect of bank angles was tested briefly from seconds 110 to 135 by angling the airfoils as if banking left; a maximum voltage of 38.8 mV and a minimum voltage of 7.7 mV was measured.

![MFC on underside of wing (taped on both ends)](image)

**Fig. 9:**
*MFCs taped at the underside of the wing, at both ends of each strip (1 sample/ 5 sec)*
During the fourth trial (Fig. 10), the MFCs were taped to the back of the side view mirror of the van. This was done to test if the aerodynamics of the wing had had any effect on the data, or if only the wind was responsible for the sensed forces. The data remained similar to the first and second trials, with a high of 134.2 mV, and a low of 7.2 mV.

The plane trial (Fig. 11) involved the attachment of the piezoelectric component to the window of the Cessna in a manner that allowed the component to flap freely in the air currents produced by the Cessna’s propeller.

![MFC mounted on side view mirror](image)

**Fig. 10:**
MFCs taped on outside of the side view mirror of the van (1 sample/ 5 sec)

![MFC on the window of Cessna 172](image)

**Fig 11:**
MFCs taped down to the inside of an open window of the Cessna 172, at only one end of each strip (1 sample/ 5 sec)
Although the MFC was configured in two different setups on the Cessna, only the data from the second setup (attached to the window) is shown in a graph form. The data from the first trial was faulty, recording zero voltage, due to a malfunctioning data logger. Figure 11 outlines the data collected from the trial when the MFC was attached to the window of the plane. The spikes in voltage correlate directly to increases in power of the plane engine. An increase in power turns the propeller faster, theoretically pushing back more air at a faster rate. The spike at 260 seconds was the cause of a simultaneous increase in power and the plane riding over a bump in the tarmac of the taxiway. The plane was consistently taxied at 600-1000 rotations per minute.

**DISCUSSION**

**Uncertainties & Error**

There were several preliminary trials (not shown) performed for both the large stationary wing model and Cessna in which the USB voltage data logger was used to gather information about the voltage generation over time. Most if not all of these trials read zero to negligible voltage generation. This data would have been noted if not for previous trials in which the same action was performed on the piezoelectric materials where the voltmeter read results far greater than the zero voltage read by the data logger. The same test was performed with a different voltmeter showing similar results. From this, it was concluded that the data logger had either a low sensitivity and was unable to recognize the changes in voltage, a slow recording rate unable to measure the rapid discharges of the capacitor or both. It also would have been ideal for the data logger to record the voltage multiple times a second, while in the experimentation it only recorded once every ten seconds and at most once a second. In future experiments, a data logger with a faster sampling rate and higher frequency limit would be ideal because the data was instantaneously fluctuating at a high frequency.

Previous experiments with piezoelectric materials in UAVs have shown the potential to produce up to 3 volts. Being that this set-up only produced a maximum of 2.3 volts on the Cessna and less than a volt on the large wing model, it was determined that there may have been an error in the methodology. It is possible that the tape used to attach the circuit to the airfoil restricted the vibration of the MFC. The airfoil itself also could have absorbed the vibrations from the wind and hindered the voltage output of the MFC. It is also possible that the act of holding the airfoil in the large airfoil model could have reduced some of the vibrations produced. In a future test, the MFC would be attached in different ways - by embedding it, making the entire airfoil out of the piezoelectric material, or attaching it in such a way that it can move freely without hindering aerodynamics. The lower voltage may have also been related to the low speeds in which the models were limited to; the Cessna only achieved a maximum speed of 11 meters per second while the large airfoil model traveled at around 7 meters per second at its top speed.

It was also found in bench tests (in which mechanical stress was applied by manually vibrating the MFC) that one strip of MFC produced less voltage than the other when individually shaken. This could have been due to a loose wire or a difference in the quality of the MFC. There is also the possibility that wiring the piezoelectric materials in parallel to one another could have created a dampening effect on the voltage generation.

**Improvements**

There are many specifications about the experimental setup which could be refined to increase the performance of the piezoelectric materials. The incorporation of an accelerometer would allow for the comparison of instantaneous voltage to speed and direction of the RC plane and the Cessna. Then, by determining turbulence or vibrational patterns of the plane under certain situations (such as a turn or an acceleration), the piezoelectric components could be placed more effectively on the airfoils.

There is also the option to embed the MFC within the airfoils rather than attaching them to the surface only. It is possible that the interior of the airfoils experience a greater vibration and as result can generate more voltage. Previous tests
have shown that internal placement can produce up to three volts (Anton, “Energy Harvesting”). There is also the variable of speed. As it was previously mentioned, the experimentation was limited by the speeds allowed by the roads and airstrips. If the models were to travel at greater speeds, they would experience a faster flow of wind over the wings and/or a greater vibration from the motor. Either change could have increased the mechanical stress or voltage output from the piezoelectric components. An actual flight with the Cessna or a large UAV would provide an increased wind speed and vibration. In future trials, it would be advantageous to test different kinds of piezoelectric material - perhaps a larger MFC would produce more voltage. It is also possible that the P1 MFC was not the most efficient energy harvester. The P2 MFC was a different piezoelectric material that was investigated and it is possible that this MFC could produce a greater voltage than the P1. Investigating different kinds of capacitors could produce different results as well. For example, a larger capacitor may have allowed the piezoelectric material to accumulate a greater voltage before discharging. A capacitor with a larger capacitance may also be able to smooth out many of the fluctuations in voltage that was observed. It must be noted that different capacitors are built for different purposes and that in this case, the capacitor used was intended to harvest small quantities of energy.

Applications

Piezoelectric generators could provide UAVs with a constant influx of electricity. This could reduce the electrical load on the battery powering the UAV and in turn save fuel by reducing the weight of the battery within the UAV. This would give the UAVs a greater fuel efficiency and longer flight endurance.

Piezoelectric materials could also be installed in other transportation sectors such as electric cars, boats, and bus systems; all of which could benefit from piezoelectric generators and would produce sufficient vibration and external air (or water) turbulence to make installation of such circuits worthwhile. The application of piezoelectric energy harvesting through other fluids has potential to expand the reach of piezoelectric material to boats, submarines, and other vehicles. While most other machines could not be completely powered by today’s piezoelectric generators, if such generators were to be attached to these machines, the vibrations given off would induce a voltage that could supplement the energy supply of the machine.

Future Considerations

For any future applications of piezoelectric materials, it is necessary to consider multiple logistical and rational roadblocks to the installation of the MFC on airplanes. First off, there is the legality issue of installing MFC on a functioning plane. The FAA does not allow extraneous materials to be attached to a plane due to safety and aerodynamic concerns. Attaching these materials to the exterior of the plane rather than embedding them or incorporating them into the production of the base material itself could cause aerodynamic problems. It is also important to consider that the MFC must not be counteractive by adding more drag to the plane. Using piezoelectric supplements would reduce the fuel load, but extra drag would require more fuel to fly the plane and would simply interfere with the plane’s performance.

Depending on the amount of voltage created by the piezoelectric material, it could be necessary to have a method to store the voltage created. At the moment, the voltage created would only be available for instantaneous usage. This is not practical on a larger scale because excess voltage would be wasted. Unlike a battery, a capacitor discharges over time and is not ideal for energy storage.

Creating a propeller or wings out of structural piezoelectric material could also maximize the voltage created from vibrations. Integrating the piezoelectric material into the source of the vibrations would be an interesting venue for further research and optimization of this type of energy harvesting.
Conclusion

It was concluded that this methodology shows potential to be scaled up and applied to commercial and military aircraft. With a maximum voltage of 2.3 V with only two small pieces of MFC, it is evident that piezoelectricity shows promise in the field of energy harvesting. The most effective location for voltage output was the window of the Cessna and although this is not a practical location for the material, it is a solid basis for future research. A strong conclusion was reached that the voltage produced is dependent on the allowable movement of the piezoelectric material.

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Appendix

Experimental Setup with RC Plane

This setup was not used in the experiment because of technical issues with the RC plane although it was ideal for simulating piezoelectric generators in small UAVs. It would have also offered a direct comparison to the results of previous UAV piezoelectric generators experiments (Anton, “Energy Harvesting”). Because it represented a major portion of the intended research, the methodology is placed here.

The plane used to test the energy harvesting capabilities of piezoelectric materials was a radio controlled (RC) Multiplex MiniMag RTF electric propeller. The rectifier circuit was secured inside the pseudo-cockpit of the RC plane and connected to the MFC patches located on the wings of the planes. A voltage data logger was connected to the capacitor on the rectifier circuit so that the instantaneous voltage could be ascertained throughout the flight; the sampling rate of the data logger was set to one sample/second.

The placement of the piezoelectric components was the same for each air foil: the piezoelectric material was placed on either the top or the bottom of the air foil at the connective point, middle, or tip of the air foil. The position of the components was changed to determine the most effective placement for maximum voltage acquisition. The piezoelectric components were attached to the air foils using electrical tape instead of embedding them within the wing. This was done to avoid tampering with the aerodynamic properties of the air foils. It was predicted that more voltage would be created if the piezoelectric material was in direct contact with the air. The fluctuating pressure of the wind could also provide a source of mechanical stress to the piezoelectric components and that the foam air foils could potentially absorb some of the impact from the wind, thus diminishing the capacity of the piezoelectric material.

In order to take into account the center of gravity of the plane, the circuit and voltage data logger were attached to the center cockpit area. Thus, the three axes of the plane - longitudinal, lateral, and vertical were balanced so as not to disturb the center of gravity (Fig. 12).

![Fig. 12: The center of gravity on a plane is the place in which all three axes are in balance (Jeppesen).](image)

To test the effect of pitch and bank angle on the voltage generation of the piezoelectric components, the movements of the plane were recorded by hand with a video camera. These records were then compared to the instantaneous voltage generation data for the specific time determined by the data logger. The comparison between the voltage created and the visual observations led to a conclusion of whether the acceleration of the plane has an effect on the voltage output of the piezoelectric material.
CITATIONS