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ELECTRICITY PRODUCTION FROM PIEZOELECTRIC PATCHES MOUNTED OVER FLEXIBLE MEMBRANE WING AT LOW REYNOLDS NUMBERS

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ABSTRACT

One of the most necessities of our age is undoubtfully to supply the ever-increasing energy demand. The world population is growing correspondingly with the developing technology and it causes more energy demand. Furthermore, when the fact that fossil fuel which is the most used energy source in the world in our age will inevitably come to an end is taken into consideration; the need to search for new energy sources has become an obligation. A piezoelectric effect is a crucial option that is used as a new energy conversion method and the researchers are trying to find ways to develop it. Thanks to their special molecular structure, the mechanical force applied to the piezoelectric materials creates an electric charge. In this way, the conversion of environmental vibrations into electrical energy can be achieved with piezoelectric materials. This experimental study aims to turn deformations and vibrational motions caused by the air on a flexible membrane wing into electrical energy thanks to piezoelectric materials. In this respect, a flexible membrane Zimmerman wing with a 1.5 aspect ratio was used. Smoke wire experiments were performed on the wing at $2.8x10^4$ and $5.6x10^4$ Reynolds numbers to capture and understand how the characteristics form of the flow over the flexible membrane surface is. Afterward, three different types of 4 piezoelectric materials were used over the flexible membrane wing and energy calculation was made over 470-ohm resistor at various Reynolds numbers and angles of attack.

Keywords: *Flexible membrane wings, piezoelectric patches, energy harvesting, low reynolds number flow.*

INTRODUCTION

In crystal physics, Jacques Curie and Pierre Curie brothers were the first to work with the Piezoelectric Materials as a research area [1]. They observed that tension and compression applied to some mineral crystals, such as quartz, tourmaline, topaz, and Rochelle salt, create a voltage in these minerals. Afterward, piezoelectric materials were developed, put on the market and started to be used in many fields. Piezoelectric materials are widely used as actuators, sensors and energy harvesters. They are used in many fields like aerospace applications, robotic applications, sports equipment (to reduce the effects of vibration), etc. [2]. Energy harvesting with piezoelectric materials has been the subject of many studies. For example, studies aiming to collect energy with the help of piezoelectric materials by using the pressure created by the vehicles on the roads have been carried out [3-5]. Sodano [6] designed a theoretical model and considered using PZT (Lead Zirconate Titanate) straps instead of the classic straps in a backpack and investigated the potential of obtaining energy for two different thickness PZT straps. As a result, he calculated about 10 mW of power for a 50 lb load in the model he designed.

Aviation applications are also an important area suitable for the use of piezoelectric materials. Unmanned aerial vehicles (UAVs) can fly automatically or semi-automatically without a flight crew [7]. These properties enable them to be used in bad weather and environmental conditions without risking human health. Many electrically powered micro UAVs include heavy rechargeable batteries. Therefore, generating energy through alternative means during flight is a preferred technology for small UAVs [8]. Among the studies carried out for this purpose, piezoelectric materials have gained considerable interest, because they can be used to collect energy over a wide frequency range and are easy to apply [9]. Anton and Inman [10] investigated the possibility of obtaining energy with piezoelectric material and photovoltaic panels in a mini UAV. They placed piezoelectric patches over the wings, two photovoltaic panels on the top of the wing and they carried out experiments. As a result, in preliminary tests during a 13-minute flight, the patches can charge the 4.6 mJ internal capacitor to 70% capacity. The results showed that the

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electrical energy that they obtain is not big enough to charge a battery. However, in the future, the method of harvesting energy by piezoelectric material in UAVs applications to provide energy for low energy subsystems can give positive results. Buyukkeskin et al. [11] studied to supply electricity form wind energy using wind stalks. In the wind tunnel experiments, a circular and four-corner wind stalks were considered for different turbulent flow conditions. Finally, the energy output was too small for the wind energy conversion systems in a market, but it was concluded that piezoelectric could be a better alternative in turbulent flows.

These days, UAVs are very important vehicles, especially in military fields. Following the job descriptions, UAVs are required to have a long stay in the air. Therefore, providing additional energy sources that UAVs can be used while in the air can contribute to the improvement of their performance. In this study, an additional energy potential that can be used in small UAVs with piezoelectric materials placed on a flexible membrane wing is experimentally investigated. Due to their small size and low speed, small UAVs often fly at low Reynolds numbers, accompanied by boundary separation, transition to turbulence and low lift-drag ratio [12-20]. Moreover, as seen in other passive flow control methods [21-28], using flexible wings can provide benefits in preventing these situations. It has been proven by many studies that flexible wings can reach higher angles of attack [8, 12, 29-35]. Açıkel and Genç [35] have reduced drag and increased lift by partially flexibility over the upper of an airfoil, thereby providing aerodynamically improvement. Therefore, it was considered using a flexible membrane wing in this study. Besides, the flexible membrane will be a very convenient base as it will allow the piezoelectric materials to be deformed easily on its surface.

MATERIALS AND METHODS

Energy Harvesting with Piezoelectric

Piezoelectric is a dielectric material which is able to also be polarized by applying mechanical stress in addition to an electrical field [2]. Crystals with piezoelectric properties produce electrical signals when subjected to dimensional deformation or vibration. This situation is called ‘direct effect’ [36]. Piezoelectric materials can be found in nature or produced by humans. Quartz, topaz, Rochelle salt are examples of piezoelectric materials found in nature. On the other hand, human-made piezoelectric materials have much more piezoelectric effect than natural piezoelectric materials. In general, human-made piezoelectric materials can classify as ceramic, polymer and composite piezoelectric materials. Piezoceramics have high piezoelectricity and a high dielectric coefficient. However, they are not flexible. Piezopolymers are flexible and can be cost-effective. However, when compared with piezoceramics, they have an average piezoelectric coefficient [37]. Composite piezoelectric materials which ceramics and polymers are used together they provide many advantages and combine the properties of piezoceramics and piezopolymers. Hence, a material with high piezoelectricity, flexible and easy to form can be obtained.

Macro Fiber Composite (MFC)

MFC is a composite smart material consisting of rectangular piezo ceramic rods compressed between adhesive layers, electrodes, and polyimide film layers as shown in Figure 1. The MFC was invented by NASA in 1999 [38]. In this study, three different MFC is used. The first one is P2 type material (the length is 28 mm; the width is 14 mm). The others are P1 and P2 type materials of the same dimensions (the length is 85 mm; the width is 7 mm). P1 type MFC utilizes d33 effect and P2 type utilizes d31 effect for operation. The ability to collect energy from deformation and vibration in a flexible membrane wing was investigated.

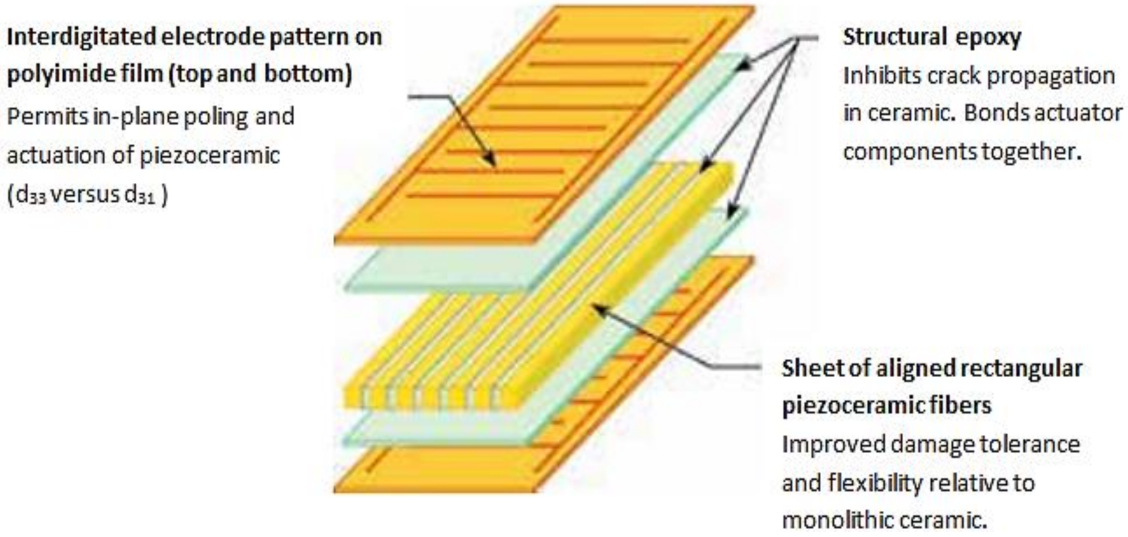


Figure 1. Schematic structure of the MFC [36]

The Flexible Wing

In this study, a Zimmerman planform with aspect ratio 1.5 was used because of some reasons as follows: First, since the piezoelectric patches are placed on them, the flat plates provide a good baseline. Also, when performing experiments on profiled wings, the results depend on both the profile, the planform, and the Reynolds number. Torres and Mueller [39] demonstrated that maximum lift coefficients can be achieved in Zimmerman wings when the vehicle's aspect ratio is between 1 and 1.5. Therefore, Zimmerman profiles were created by combining the semi-circle with the semi-ellipse (semi-major radius =75 mm, semi-minor radius =50 mm). Dimensions of this Zimmerman wing were proposed and used by Arivoli and Singh [40]. For the experimental study, a wing frame with these dimensions has been manufactured. Then the membrane was stretched to this frame and the flexible wing shown in Figure 2 was prepared. The membrane material used in the study has 2.2 MPa Young's modulus (E), 0.2 mm thickness and 1 g/cm^3 density (ρm) [29-30].

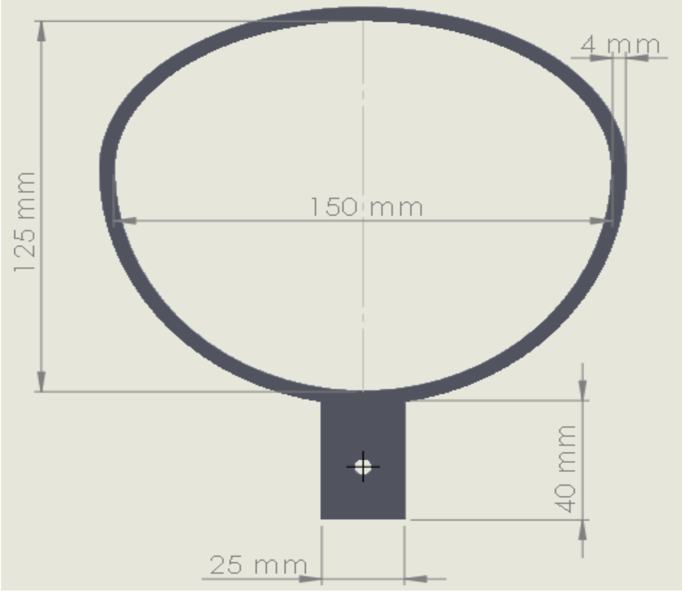


Figure 2. Zimmerman flexible wing

RESULTS AND DISCUSSION

Smoke Wire Experiments

The flow visualization smoke-wire experiment was carried out at various angles of attack (α) and Reynolds (Re) numbers of $2.8x10^4$ and $5.6x10^4$. These Reynolds numbers are suitable for the low Reynolds regime to capture and understand how the characteristics form of the flow over the flexible membrane surface is. Since the oil drops did not attach on the wire at $Re=11.2x10^4$, smoke sheets could not be obtained and therefore smoke-wire experiment was not performed under this flow condition.

All experiments were done in suction type low speed wind tunnel. The cross-sectional area of the test chamber is covered by optically transparent walls measuring 500 mm x 500 mm to observe flow patterns over the flexible membrane wing easily. Turbulence intensity of the tunnel are under 1% for all wind speeds [41].

Regarding the flow visualization, as shown in Figure 3, the smoke-wire method in the wind tunnel was performed since it was a reliable and simple way to observe flow patterns over flexible wing surfaces. 0.3 mm copper wire was strained between upper and lower square test chamber, and resistive heating was utilized in conjunction with machine oil for heating. Once oil drop was formed from top to bottom, resistive heating was functioned to coat oil drops. A compact camera that was outside of a test chamber was used to capture related images during the experiments.

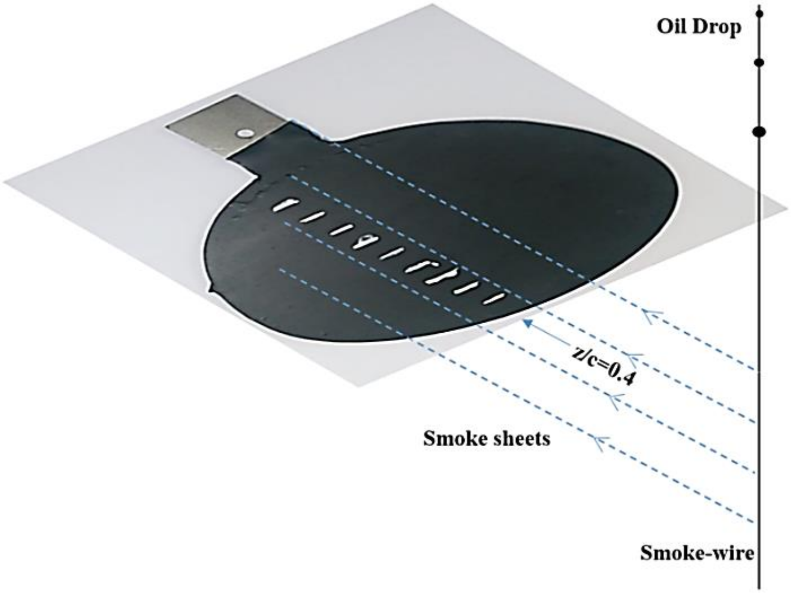


Figure 3. Position of smoke wire on membrane wing

As seen in Figure 4, when the line of smoke sheets was at z / c = 0.4, the separation bubbles formed at moderate angles of attack, causing earlier separation from the rear of the airfoil at low velocities. As a result, stall occurred at $Re=2.8x10^4$. As Reynolds number increases, inertial forces become more dominant than viscous forces. Therefore, a more stable flight condition is obtained and flow separation from the wing surface is observed at higher angles of attack. In addition, the deformation of the flexible membrane at high angles of attack at $Re=5.6x10^4$ was easily observed, while the flow at $Re=2.8x10^4$ did not cause a serious deformation in the wing.

When the line of smoke sheets was at z/c= 0.1, the changes of tip vortices with the angles of attack are demonstrated in Figure 5. Since the aspect ratio is low and the effect of the tip vortices on both sides affects the entire wing, the flow structure on the wing has changed.

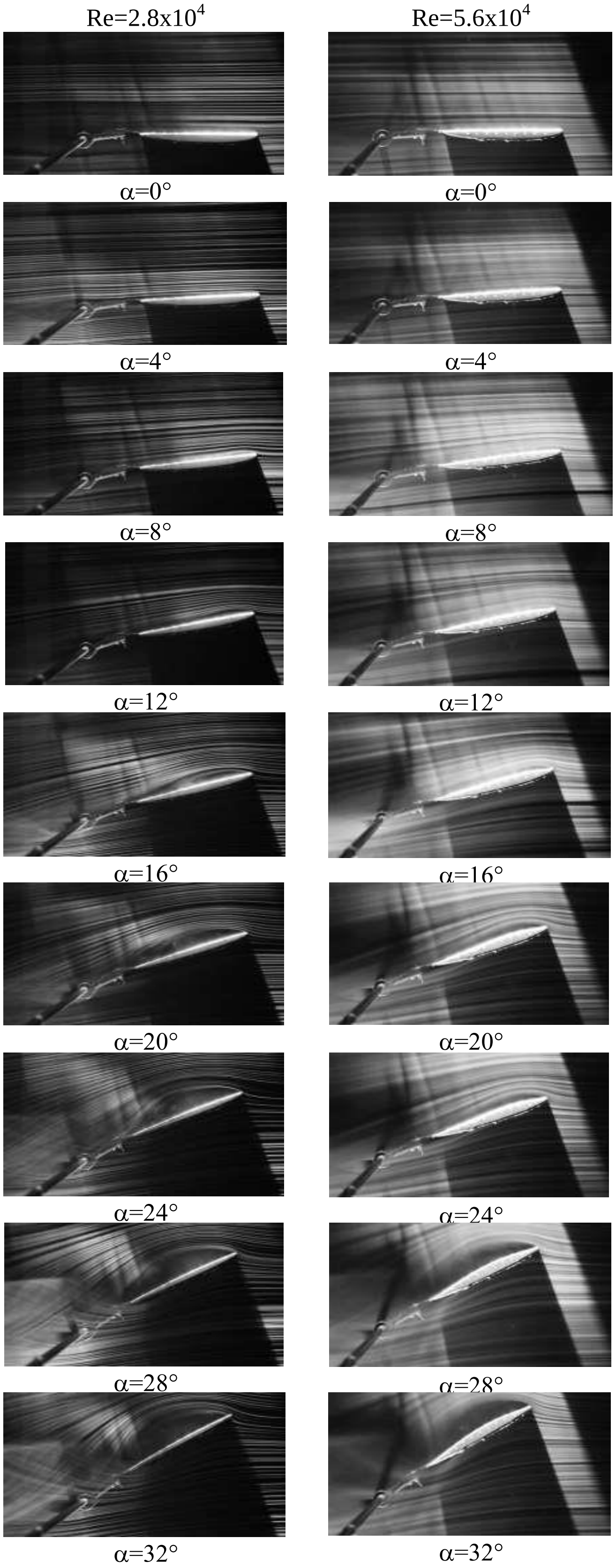


Figure 4. Flow visualization from smoke-wire experiment at z / c = 0.4

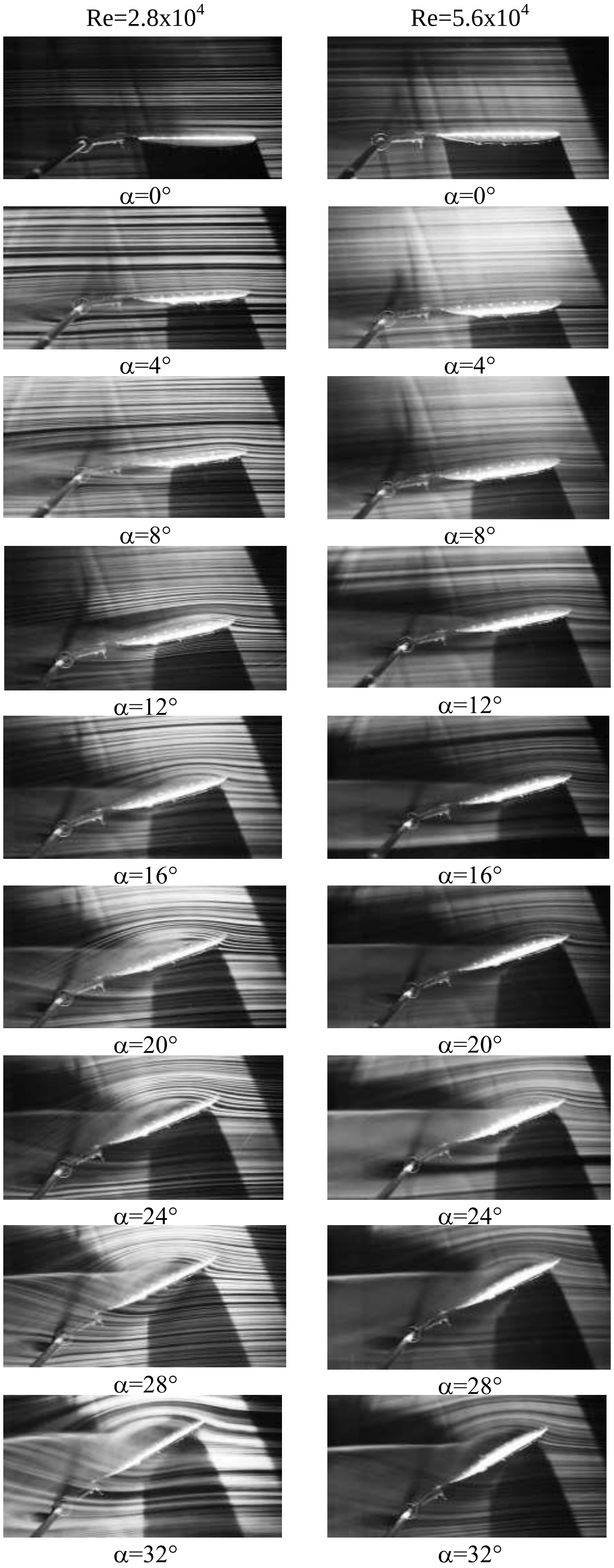


Figure 5. Flow visualization from smoke-wire experiment at z / c = 0.1

Calculation The Energy Values Obtained from Piezoelectric Materials Over a Flexible Membrane Wing

Piezoelectric patches were placed on the membrane wing as shown in Figure 6, considering the previous studies [42] and the dimensions of the piezoelectric patches. After piezoelectric patches were placed on the wing, the wing was connected to the wind tunnel and the current expression in Equation 2 for energy calculations was measured utilizing a multimeter as seen in Figure 6. Four piezoelectric materials on the wing are connected in parallel to increase the current value. Then, the current values were recorded for 10 seconds on a resistor with a value of 470 ohms. Since no significant change was observed in the measured current values after the system became stable, calculations were made using the averages of the current values recorded for 10 seconds.

$$P = I_{rms}.V_{rms} = (I_{rms})^2.R \tag{1}$$

$$E = I_{rms}.V_{rms}.t = (I_{rms})^2.R.t = P.t \tag{2}$$

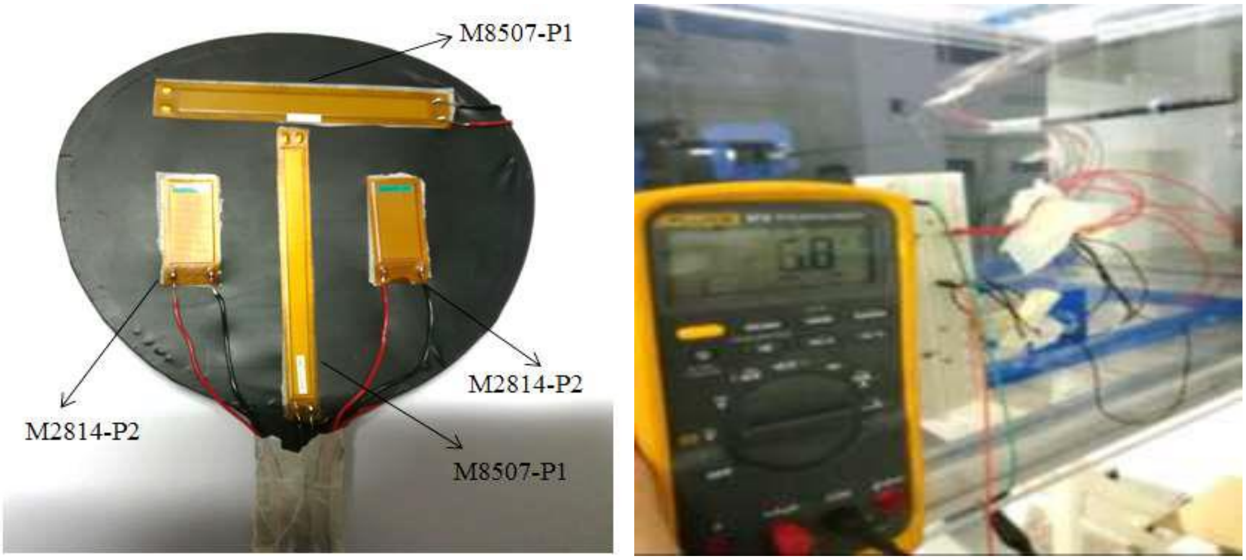
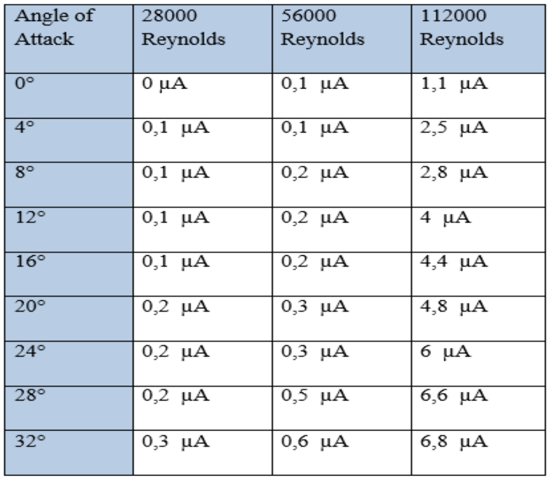


Figure 6. Positions of piezoelectric materials on the membrane wing and current measurements

Afterward, current values were measured depending on the angles of attack, as shown in Figure 7 and presented graphically at different Re numbers. Then, the electrical energy obtained by using this current value was calculated and the graphic in Figure 8 was obtained. As seen in the result, the electrical energy obtained from piezoelectric materials increased as the Re number and the angle of attack of the wing increased. Especially, the increase of wind speed at Re=11.2x10^{4}caused more deformation in the flexible membrane wing provided a significant increase in the current obtained. The graph shown in Figure 8 shows that the greatest value of the energy obtained is at Re=11.2x10^4 and α=32°. Accordingly, the maximum electrical energy obtained from 4 piezoelectric patches for 10 seconds was 220 nanoJoules. More likely, the further increase in the Reynolds number will increase electrical energy. The flexible wing that used in this study provided great advantages in this sense. Because if a rigid wing was used instead of the flexible wing, the stall angle would be smaller. Therefore, the wing would not be able to reach higher angles of attack and the electrical energy would be less. In addition, the deformations occurring in the flexible wing enabled the thin and flexible piezoelectric materials to move and deform with the membrane wing surface easily, thereby increasing the energy obtained.



Angle of Attack	28000 Reynolds	56000 Reynolds	112000 Reynolds
0°	0 μA	0,1 μA	1,1 μA
4°	0,1 μA	0,1 μA	2,5 μA
8°	0,1 μA	0,2 μA	2,8 μA
12°	0,1 μA	0,2 μA	4 μA
16°	0,1 μA	0,2 μA	4,4 μA
20°	0,2 μA	0,3 μA	4,8 μA
24°	0,2 μA	0,3 μA	6 μA
28°	0,2 μA	0,5 μA	6,6 μA
32°	0,3 μA	0,6 μA	6,8 μA

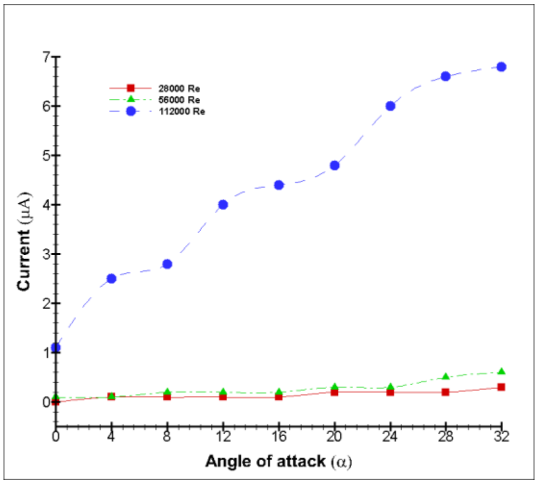
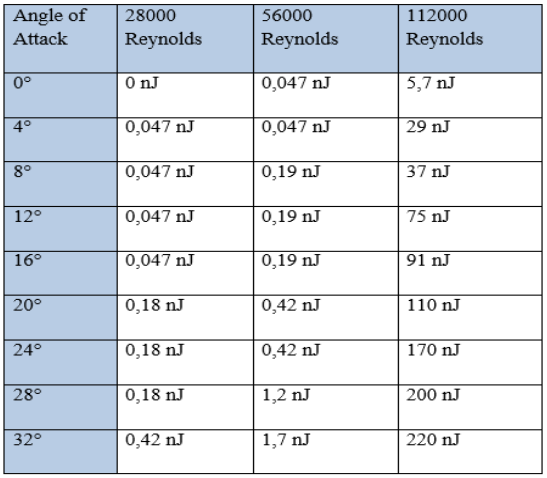


Figure 7. Variation of current depending on α and Re



Angle of Attack	28000 Reynolds	56000 Reynolds	112000 Reynolds
0°	0 nJ	0,047 nJ	5,7 nJ
4°	0,047 nJ	0,047 nJ	29 nJ
8°	0,047 nJ	0,19 nJ	37 nJ
12°	0,047 nJ	0,19 nJ	75 nJ
16°	0,047 nJ	0,19 nJ	91 nJ
20°	0,18 nJ	0,42 nJ	110 nJ
24°	0,18 nJ	0,42 nJ	170 nJ
28°	0,18 nJ	1,2 nJ	200 nJ
32°	0,42 nJ	1,7 nJ	220 nJ

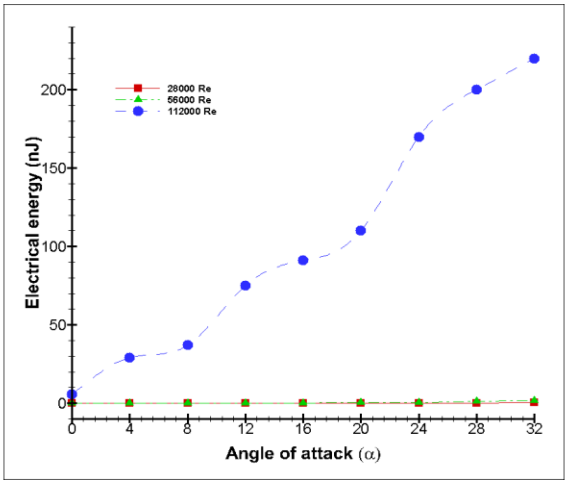


Figure 8. Variation of electrical energy depending on α and Re

CONCLUSION

This experimental study aims to investigate the potential of piezoelectric patches mounted over the flexible surface of micro UAVs to obtain electrical energy from membrane vibrations during the flight. In this respect, a flexible membrane wing was used, and experiments were carried out for various α and Re. The results show the following points:

- The potential of piezoelectric materials with regards to the production of energy on flexible wings was higher especially at the higher angles of attack and at the higher wind speeds.
- With the increasing of Reynolds number, the increasing of the flow velocity around the wing causes more deformation in the membrane material. Additionally, the wing with a low aspect ratio causes the tip vortices to play a dominant role especially at the central region of the wing. Thus, the obtained electrical energy increases.
- This study revealed that utilizing different types of piezoelectric patches on the flexible wing provides a low electrical energy output, especially in small size wings.

Consequently, the obtained electrical energy was very low and it was not possible to use it directly. The fact that the wing surface was small for limited the number of the piezoelectric mounted over the flexible membrane wing. Also, it can be expected that using a larger wing over which more piezoelectric mounted, more energy can be obtained. There are very limited studies conducted about the use of piezoelectric materials over the flexible membrane wings. Therefore; more studies about the use of piezoelectric materials over the flexible membrane wings are required. Thus, the low energy demand of the small but very essential equipment such as the camera on the UAVs can be obtained from piezoelectric materials. Moreover, the biggest advantage of obtaining energy in flexible wings with piezoelectric materials is that there will always be a vibration in the wings during flight time. So continuous energy can be obtained. Therefore, using a PMIC (Power Management Integrated Circuits) that is suitable for the current and measured voltage values can make the energy possible to be used for applications that require low power.

In light of the data obtained from this study, the use of the energy obtained from piezoelectric materials by designing a PMIC integrated circuit is among our future goals.

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