THE DESIGN AND DEVELOPMENT OF AN ACTIVE SMART WING MODEL

FINAL REPORT

SUBMITTED TO:
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Dr. Stearman,

ATAK Technologies submits this final report, “The Design and Development of an Active Smart Wing Wind Tunnel Model,” as an account of the work completed this Spring semester 2003. Chronicled in this report is the research completed on the topics surrounding the implementation of active wing technology and the means necessary in carrying out the testing of a wind tunnel wing model. The report contains the ATAK Technologies team organization and the current semester objectives. This report also includes researched theory as well as system and model designs. In addition, a description is included of the detailed description how of the ATAK model functions, as well as a discussion on possible testing procedures. As a conclusion to the report, a layout of the work completed and recommended work for future groups is incorporated. If there are any questions regarding any aspect of this report, please contact the team leader, Thomas Ayers, and all inquiries will be answered.

Sincerely,
ATAK Technologies
Abstract

The design and modeling team of ATAK Technologies has been working on designing and building a model for research in the study of the effects on lift coefficients by oscillating leading and trailing edge flaps as opposed to conventional high lift devices. The current model design was modified to include active control surfaces and an electromechanical motor. The model will specifically be used by future groups to investigate the aerodynamic benefits during low speed, high angle of attack flight. Theoretically, oscillating flaps at high frequencies would cause the flow to remain attached for a longer period of time, therefore preventing stall at speeds below conventional stall speeds. Previous research on a simplified conceptual model indicated that the model can properly oscillate its flaps at frequencies up to 15 Hz. ATAK Technologies had several objectives for the active wing project. First, an active wing model was designed and constructed. After which, ATAK then attached the wing model to a controller and power system. Proper testing equipment has been determined for the desired scenarios in which the wing model will be equipped with various testing and measurement equipment. ATAK Technologies concluded the semester by constructing a final report and presentation of this semester’s achievements to the project supervisor, Dr. Ronald Stearman.
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  The engineering group responsible for the active wing project during the Spring 2002 semester. Their research and experimentation was integral to the completion of the objectives set forth by ATAK Technologies.
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1.0 Introduction

Only a few major changes to the control devices of wings have been implemented since the beginning of powered flight in 1903. Trailing edge flaps had a major impact allowing, in some cases, for the lift coefficient to be quadrupled. Later, leading edge flaps and slats were developed to further increase the coefficient of lift. No major advancements have been made since that time, although this is about to change with the development of oscillating leading and trailing edge flaps, which is one of the concepts behind the active aeroelastic wing.

The active aeroelastic wing utilizes control surface movement in order to improve the performance of the aircraft. This technology uses oscillating flaps to cause the airflow across the airfoil to remain attached longer on the wing, which in turn increases the lift coefficient and allows the airfoil to stall at a higher angle of attack for a given speed. Traditionally the effectiveness of the control devices of the wings on airplanes is low during high speed flight. This decrease in efficiency is caused by latent aerodynamic forces which adversely affect the foil along the airfoil. The roll performance of the aircraft is also limited due to counteractions between the ailerons at high speeds. Furthermore, a phenomenon known as limited cycle oscillation (LCO) can develop during flight and cause severe structural problems by increasing the fatigue on the aircraft wings. Active aeroelastic wing concepts can be tailored in order to control wing twist to improve roll maneuvering without using other control surfaces. These concepts can also be useful by negating the effect of LCO on the aircraft wings. All of these characteristics
are desirable when maximizing the aerodynamic performance of airplanes. A model of an active aeroelastic wing must be constructed in order to continue research on the effects of multiple frequencies and angles of deflection on aircraft performance.

1.1 Past Research Work

Active wing technology has been researched intensively prior to this project. The work that ATAK Technologies will pursue during this semester is heavily dependent on the accomplishments and recommendations of the previous engineering teams at the University of Texas at Austin.

1.1.1 Spring 2002

Active Wing Group (AWG) initiated the active aeroelastic wing study at the University of Texas at Austin. The most significant accomplishment was the assembly and refurbishing of the F-111 wing-tail model provided by Randall Bolding [1]; during which it was found that the hydraulics system required maintenance. AWG then employed Austin Hydraulics to repair and certify the hydraulic pump, hoses, and servos located in the hydraulic actuator system. Another achievement of AWG was the planning and construction of a mounting platform for the wing model. Furthermore, an analog controller system was retrieved, cleaned, and repaired in order for future use in controlling the active wing model. The final contribution to the active wing study by AWG was the extensive research into active wing research. This research included LCO research and the current aeroelastic studies. Information gathered from NASA, the United States Air Force, and the Southwest Research Institute were compiled in order to
“define and enhance possible avenues of investigation that future research groups may choose to pursue with this wing model” [2].

At the conclusion of the AWG report several recommendations were made for any future groups developing active wing technology. The hydraulic system was a major concern. It had been left for service at Austin Hydraulics, however, not much work on the system had actually been performed. Furthermore, it was determined that the stabilator still required refurbishing. Finally, AWG specified that the study of limited cycle oscillation and control reversal phenomena would “represent excellent scientific pursuits” for future groups investigating active wing technology [2].

1.1.2 Summer 2002

Active Wing Technologies (AWT) completed and improved upon the model work provided by AWG. The constructed model consisted of several components such as the wing structure itself, the root-wing stabilator, the nose and stabilator wedges, and the malfunctioning hydraulic system. Despite the extensive effort of AWT to repair the faulty hydraulic system, the necessary component proved to be a liability. It was decided to replace the hydraulics with a more efficient and reliable power supply. A large portion of the work completed by AWT was in the field of research. Theory was compiled and developed concerning LCO, increasing the maximum lift coefficient, and various actuator power supplies to replace the broken hydraulic system. During this time Dr. Stearman approached AWT with information concerning the increasing of the lift coefficient of fighter aircraft. Information and recommendations were sought regarding the aeroelastic benefits that could be achieved using active wing technology. Additionally, analog and
digital control systems were researched. The final achievement of AWT was the construction of a digital AutoCAD schematic of the wing model provided by Randall Bolding [3].

At the conclusion of the AWT report several recommendations were made for any future groups developing active wing technology. The power supply system was a major concern. AWT determined that a system capable of frequencies above 56 Hz would have to be achieved by the power system. A power supply with this ability will need to be found. Finally AWT specified that mathematical models of the active wing processes must be formulated in the form of Bode plots in order to optimize any future controllers design [3].

1.1.3 Fall 2002

Active Wing Engineering (AWE) completed a great deal of work concerning the design of the model. The beginning of their project consisted of familiarizing themselves with the aerodynamic theory behind oscillating flaps. After understanding the design concepts, AWE selected the electromechanical actuation system components necessary to operate the active wing model. With this information, the preliminary wing designs were completed for continuous and segmented rod models. AWE then constructed both models, attaching the simple actuation system to both systems. AWE verified the functionality of their design using preliminary testing of the continuous rod model at desired frequencies [4].

At the conclusion of the AWE report, several recommendations were made for any future groups developing active wing technology. The completion of the preliminary
testing of the segmented rod model was the first priority. Emphasis was also placed on the redevelopment of a design consisting of a model accommodating both leading and trailing edge flaps. AWE also indicated several problems concerning the mass balance of the model which needed future attention. Finally, AWE specified that measurement instrumentation must be included in the final active wing model [4].

1.2 Project Objectives

The ATAK Technologies team has several objectives to complete during this semester.

- To design an F-18 wing model using AUTOCAD
- To construct an operational F-18 wing model
- To properly attach the wing model to a controller capable of oscillating the flaps at a designated range of frequencies
- To determine the desired scenarios for which testing is needed
- To determine the proper testing procedures
- To test the wing model in the wind tunnel
- If possible, analyze the gathered data and derive conclusions from those results

1.3 ATAK Technologies Team Structure

The ATAK Technologies team structure is described in Figure (1.1) below. Thomas Ayers has a dual role as project leader and assistant engineer for testing procedures. Vu Tran will be in charge of testing the model as the senior testing specialist. Kevin Mackenzie will be overseeing the modeling and design aspects during our project timeline as the senior design and modeling specialist. Robert Aguirre will be researching
the history and current developments in active wing technology as the senior research specialist.

Figure 1.1: ATAK Technologies Team Structure
2.0 Background Theory

Before analyzing how oscillating flaps can benefit flight characteristics, such as lift coefficient, it is imperative to provide the background theory necessary for the development and understanding of this project. First, basic aerodynamic forces are discussed; after which, the background behind lift-enhancing devices is discussed; this is followed by a brief explanation on flutter. Limit Cycle Oscillation (LCO) information is discussed as well, in regards to how it affects the aerodynamic forces. Lastly, information on oscillating flaps is discussed.

There are four aerodynamic forces associated with flying objects; they are thrust, lift, drag, and weight. The scope of this project is to investigate the effects of oscillating flaps on lift. Lift and drag are two essential forces associated with flight; however, lift is the only essential force necessary for flight.

When an aircraft is in flight, air flows around the airfoil and creates two different velocity regions along the top and bottom surfaces of the wing.
As seen in Figure 2.1, when air molecules approach an airfoil, the molecules that flow over the top speed up; this yields a high velocity region along the top surface when compared to the velocity region along the bottom surface.

Based on the equation

$$P + \frac{1}{2} \rho V^2 + \rho gh = const \ [4]$$

from Bernoulli’s principle, it can be seen that as the velocity increases, the pressure must decrease along the top surface of the aircraft wing. This occurs vice versa in regards to the bottom surface of the aircraft wing, assuming that the variations of air density (\(\rho\)), gravitational force (\(g\)), and altitude are negligible when in constant altitude flight. This phenomenon implies that the bottom surface of the wing experiences a high-pressure region and the top surface experiences a low-pressure region. This pressure gradient
generates an upward force perpendicular to the surface of the wing, providing a lift. The aerodynamic force, lift, can be defined by the equation below:

\[ L = \frac{1}{2} C_L \rho S V^2 \]  

Eq. 2.2

where, air density at local altitude is denoted as \( \rho \), \( S \) is the wing area, \( C_L \) is the coefficient of lift, and \( V \) is the velocity of flight through the air. The amount of lift generated by the wing depends on the shape of the cross-section of the airfoil and the inclination with respect to the flow direction. The inclination of the wing with respect to the flow is cited as the angle of attack, also described as the angle between the chord line of the airfoil and the flow direction. Studies have implemented and stated that the amount of lift can be increased by increasing the angle of attack. The lift varies almost linearly for small angles of attack (within +/- 10 degrees) \([6]\). For higher angles of attack, however, the increase in angle of attack has a negative effect on the lift. As described above, the air molecules stick to the surface of the wing as it moves through the air, which creates a layer of air near the surface of the wing, called a boundary layer. When an aircraft flies at a critical angle of attack, the boundary layer detaches from the surface of the wing and the flow becomes turbulent, which causes the aircraft to dramatically loose lift and stall.

Lift coefficient is generally used to model all of the complex dependencies of shape, inclination, and flow conditions on lift. Lift analysis can be simplified by analyzing lift coefficient alone, which is governed by the equation below:

\[ C_L = \frac{L}{0.5 \rho S V^2} \]  

Eq. 2.3
Generally speaking, lift coefficient is a nondimensional value and dependent to the angle of attack and the cross-section shape of the airfoil. The relationship between lift coefficient and angle of attack can be expressed by the $C_L$ vs. Angle of Attack plot below, which was obtained from several experiments. [7]

![Graph showing the relationship between lift coefficient and angle of attack](image)

**Figure 2.2:  Relationship Between Lift coefficient and Angle of Attack $\alpha$ [6]**

As seen from the plot, the lift coefficient has a linear relationship with the angle of attack. However, when the lift coefficient reaches the maximum value, which is at the critical angle of attack, it starts to decrease if the angle of attack continues to increase. When the lift coefficient passes the maximum value, the aircraft starts to stall due to the separation of the boundary layer from the top surface of the wing. The velocity at which the aircraft stalls, $V_{Stall}$, is defined by the equation below:
where the weight of the aircraft is denoted as $W$, and the maximum value of lift coefficient is denoted as $C_{L_{\text{max}}}$. The stall speed determines the minimum airspeed an aircraft can fly to have a sufficient amount of lift in order to sustain the weight of the aircraft during unaccelerated flight. In the design process, weight is minimized, and the lift coefficient is the ideal parameter to optimize in order to reduce the stall speed. When an aircraft lands on an aircraft carrier, it wants to slow down, so the nose is pitched up, and the flaps are deflected down to decrease the aircraft’s speed and to gain a sufficient amount of lift in order to sustain the aircraft’s weight. If the angle of attack is increased to a critical value, there is a possibility that the aircraft will stall. Therefore, techniques have been used in order to increase the lift coefficient, and thus obtain more lift.

2.1 Lift-Enhancing Devices

Leading and trailing-edges flaps and slats are used to increase lift coefficient. Figure 2.3, found below, is an example of how flaps are used during different flying conditions. The flaps change the pressure distribution on the airfoil due to the increase in chord length and camber. In addition, the flaps increase the area of the wing perpendicular to the airflow direction in order to increase lift and decrease the stall speed. Newtonian approach and Thin Airfoil Theory can be used to describe how increasing the camber has the possibility of increasing the lift. “The Newtonian approach states that lift is the result of pressure reactions that oppose the turning of flow, thus higher lift is
caused by greater turning.” [4] Notice from Figure 2.3, the flap deflection angle at takeoff is smaller than at landing.

**Figure 2.3: Flap Deflection During Different Flight Conditions [6]**

At zero angle of attack, the Thin Airfoil Theory describes the camber effects on lift using the equation below:

\[ C_L = 2\pi \alpha_{3/4} \]  

Eq. 2.5

where \( \alpha_{3/4} \) is the angle between the chord axis and the line tangent to the airfoil as seen from Figure 2.3.

**Figure 2.4: Thin Airfoil Example [7]**
As the camber increases, the angle $\alpha_{\frac{3}{4}}$ also increases, and thus the lift coefficient increases as well. Slats are used as an opening at the leading edge of the airfoil to allow high pressure air underneath the airfoil to combine with the air on the top surface of the wing, which increases the energy of the boundary layer. "By increasing the energy of the boundary layer, the wing can sustain higher angles of attack and a higher maximum coefficient of lift." [8] Figure 2.5 is an example of a slat that is located at the leading edge of the airfoil.

![Figure 2.5: Airflow Through Slat in Airfoil](image)

2.2 Flutter

Aircraft wings are flexible and easily to bend or twist during flight due to the pressure of the airflow acting on the structure; however, aircraft wings are designed to withstand high loads. During high speed flights, the static air loads can cause the wing tips to flap or oscillate in a periodic manner. As the speed increases, the air loads continue feeding the elastic motion of the wing and increases the oscillation amplitude, thus increasing the air loads, which eventually exceed the structural strength limit causing
wing damage. This aerodynamic effect is called flutter. The speed at which flutter occurs is cited as flutter speed. Flutter is the self-excited oscillation in which energy is absorbed by the lifting surface from the air stream [10]. When the structure flutters, it reaches an unstable state, and the oscillation condition diverges. When the aircraft speed is below the flutter speed, the flutter oscillation is always damped, thus it remains stable. The amplitude of vibration remains constant when the speed of an aircraft is equal to the flutter speed. Active flutter suppression is examined by using an automatic control system to actuate the control surfaces on the wing reacting to structural motion. The active flutter suppression changes the characteristics of the aeroelastic modes, and that, in turn, causes flutter to occur at a much higher flight velocity. However, while theoretical studies concerning active flutter suppression exist, flutter suppression still remains highly experimental.

2.3 Limit Cycle Oscillation:

One of the contributions the Spring 2002 Active Wing group had on this continuous project is the research on Limit Cycle Oscillation. To summarize, Limit Cycle Oscillation is a limited-oscillating response of an aircraft that is caused by interactions between aircraft system forces. Unlike the oscillation amplitude in flutter which increases to infinity when the system becomes unstable, the oscillation amplitude in Limited Cycle Oscillation does not infinitely increase.
“The oscillation achieves a finite amplitude and cannot grow any larger due to some nonlinear limiting mechanism. These mechanisms destroy the ability of the forces to continue to grow in proportion to deflections, thus the mechanisms are nonlinear in nature.” [9]

This implies the Limit Cycle Oscillation can cause cyclic flow separation over the wing during flight, which increases the angle of attack, therefore no longer generating more aerodynamic forces on the wing surfaces. Other nonlinear limiting mechanisms also occur in aircraft structure.

**Oscillating Flaps**

Many lifting devices are used to increase the lift coefficient when aircraft fly at high angles of attack. However, conventional leading and trailing-edge static flaps do not enhance the lift or prevent the aircraft from stalling when it flies at a critical angle of attack. The oscillating flaps effect on lift coefficient is a new technique and has been studied recently. ATAK Technologies’ proposed objective for this semester is to study this phenomenon.

The Active Wing Technologies group from Summer 2002 mentioned in their final report that the applications of oscillating flaps have helped control the separation of the flow over the wing surface. However, they concluded that the results are not the same for all flying conditions. Professor Dr. F.B. Hsiao at National Cheng Kung University in Taiwan has also been studying this subject matter, and he has written some technical reports as well. In one of his reports, Dr. Hsiao has indicated oscillating flaps create
vortices that “enhance the momentum transfer between the free-stream and the boundary layer” and thus increases the “reattachment of vortices” [11].

During flight, there are two flow types that generate lift force to the wing; they are attached-flow type and detached-vortex-flow type. The difference in the circulations of upper and lower boundary layers in the attached-flow type generates the lift force near the quarter chord of the airfoil. In addition, rolled-up leading-edge vortices in the detached-vortex-flow type provides further lift to the airfoil. However, when a higher angle of attack is achieved to provide more lift, the vortices formed become uncontrollable through unsteady separation, vortex shedding, and vortex breakdown. Control of vortices is essential if higher angle of attack is to be reached without dynamic stall occurring. The two possible methods of controlling the vortices are flow separation control and flow reattachment control; these methods can be conducted at different stages of the vortex formation.

First, during a stage of vortex evolution, the vorticity strength is described by the boundary vorticity flux below, which represents the balance between pressure force, inertial force, and viscous force along the tangential direction. [12]

\[
\sigma = n \times \rho a_b + (n \times \nabla) \cdot (\Pi \cdot I + \tau \cdot n)
\]

Eq. 2.6

where:
\( n \rightarrow \) unit normal vector
\( a_b \rightarrow \) solid wall acceleration
\( \Pi = p - (\lambda + 2\mu) \nabla \cdot u \rightarrow \) dynamic “compressing variable”
\( I \rightarrow \) unit tensor
\( \tau = \mu \omega' \times n \rightarrow \) skin friction
\( \omega' = \omega - 2W \)
\( W \rightarrow \) wall angular velocity
\[ \lambda \rightarrow \text{second viscosity} \]
\[ \mu \rightarrow \text{viscosity} \]

Controlling the boundary vorticity flux controls the flow separation by using the possible methods shown below:

1.) Proper design of the airfoil or wing geometry, and application of suction and blowing to control tangential pressure gradient

2.) Modify the local \( \tau \)-field near critical points, or application of local blowing or suction to control skin-friction field

3.) Introduce a local movable wall (e.g. an oscillating flap)

Secondly, flow separation should be controlled prior to the unfavorable formation of vortices due to separation from a smooth surface. “It is always less effective to alleviate an already formed stable vortex than to prevent its formation.” [12] The enstrophy flux, which describes the steady separation from a smooth surface, is as follows:

\[ \eta = \mu \frac{\partial}{\partial n} \left( \frac{1}{2} \omega^2 \right) = \omega \cdot \sigma = \frac{1}{\mu} \tau \cdot \nabla p + \mu \omega \cdot \nabla n \cdot \omega \]

Eq. 2.7

Where \( \eta > 0 \) implies an enstrophy source, a newly formed vortex strengthens the existing one; while \( \eta < 0 \) implies a sink, where a newly formed vortex cancels the existing one. Because flow separation is indicated by a sink, it can be eliminated by sufficient suction near the separation. [12]

If a boundary layer is already separated, then control of its reattachment is needed. This is feasible using the unsteady surface excitations. Many configurations of basic
two-dimensional wings were proposed to capture vortex, and thus achieve a sustainable high lift at high angle of attack. For example, a Kasper wing as shown in Figure 2.6 was successfully flight tested. However, in this example, the serious instability problem was noticed, (a large amount of jet blowing or suction was required to stabilize the captured vortex) and the crucial role of unsteadiness was ignored.

![Detached vortex flow on Kasper wing](image)

**Figure 2.6:** Detached vortex flow on Kasper wing [12]

Another approach which successfully suppressed separation by oscillating a flap tangentially near the separation point was proposed. The receptivity mechanism of the tangential oscillation mode is straightforward compare to acoustic excitation (a method that use acoustic wave to suppress separation). In the experiment conducted by Zhou and Felnholz, the angle of attack and the lift increases up to 27° and 60% respectively; when a small leading-edge oscillating flap was used it forced the shear layer, which was separated from the leading-edge, to attach back to the airfoil surface. Furthermore, the excitation frequency that yielded the highest lift coefficient for α = 27° was obtained around 15 Hz. The relationship between the average velocities at both sides of the boundary layer (\( \bar{U} \)), the momentum thickness of the vortex layer (\( \theta \)), and the excitation frequency (f) is described by the equation below:
In one of the works from Kobayakawa, Kondo, and Suzuki at Kyoto University in Japan, the flow behavior around the airfoil is proved to be controlled by the surface oscillation. The use of surface oscillation can enhance the lift force, and thus prevent leading edge stall of airfoil at high angle of attack. [15] One of the methods that generates surface oscillation is the use of Poly Vinylidene Flouride (PVDF) film on the airfoil surface. The PVDF has strong dielectric property under an electric field that produces a stress when polarization changes in an adverse direction. Figure 2.7 is an example of the configuration of the film embedded on the airfoil surface, and during the experiment, the film oscillates vertically at average amplitude of $11 \mu m$.

![NACA-0012 airfoil with surface oscillation.](image)

From this experimental result, the lift coefficient and stall angle of attack increased in the oscillation condition. As seen from Figure 2.8, in a non-oscillated condition, maximum lift coefficient, $C_{l_{\text{max}}}$ was 0.72 and stall angle of attack was $14^0$. However, in the oscillated condition, the maximum lift coefficient and stall angle of attack increased to 0.76 and $15^0$ respectively. Furthermore, indicated from Figure 2.9, the maximum increment of $C_{l_{\text{max}}}$ was achieved around an oscillation frequency of 50 Hz.
Figure 2.8: $C_l, C_d$ vs. $\alpha$ in the experiment at $Re = 10^5$. [10]

Figure 2.9: $C_{l_{max}}$ vs. oscillation frequency in the experiment [10]

The improvement of lift force was further explored in the numerical simulation. In the non-oscillated condition, the lift coefficient $C_l$ dropped from $C_{l_{max}} = 1.38$ ($\alpha = 14^0$) to 1.15 at the stall angle of attack, $\alpha = 15^0$. However, in the oscillated case, although the lift coefficient could not exceed 1.38, it increased to 1.31 at $\alpha = 15^0$ as seen from Figure 2.10.
Figure 2.10: Cl, Cd vs. $\alpha$ (Re = $3 \times 10^6$) [15]

The lift force decreased significantly for the non-oscillated case when compared to the oscillated case due to flow attachment which was enhanced by surface oscillation. Velocity vectors and density contour illustrated in Figure 2.11 implied that while a strong vortex is shed, and flow separates from the surface for a non-oscillated case, the flow stays attached to the surface and the vortex shed is relatively small for the oscillated case.
Because different Reynolds numbers were used in numerical simulation and wind tunnel testing, the comparison can be done only qualitatively. However, the effort to improve lift force at high angle of attack using surface oscillation was successful in both numerical simulation and wind tunnel testing. The lift coefficient increased and stall angle was delayed when surface oscillation is used. Furthermore, it may be presumed that the oscillation energy is proportional to the Reynolds number in order to control the separated flow completely. [15]

Another recent study was conducted by the University of Cincinnati Ohio (UCO) researchers Q. Deng and I. Gursul to test the effects of oscillating flaps on leading-edge vortices and vortex breakdown over a delta wing with upward-deflected flaps. These
individuals ran different tests to compare the effects of stationary and oscillating leading-edge flaps on the breakdown location of vortices. Different flap angles were used to see the differences between the two types of leading-edge flaps. At oscillation flap amplitude,

$$\delta = 120^0 + 60^0 \sin wt$$

Eq. 2.9

where $k = \alpha c / 2U_\infty = 0.4$ and $\alpha = 30^0$, 

“The oscillation of the flaps produces delay of breakdown in some part of the cycle compared to the quasi-steady case, but it also advances breakdown in other parts of the cycle.” [16] In addition, at oscillation flap amplitude, $\delta = 90^0 + 10^0 \sin wt$, $k = 0.4$, and $\alpha = 20^0$, the breakdown location found at the trailing-edge of the wing, whereas for the stationary flap the breakdown location is over the wing. Another test was conducted within the same parameters as the previous test, but it used a higher angle of attack. The results indicated that the breakdown location did not change that much compared to the location at $20^0$. In conclusion, when the breakdown location occurs upstream of the trailing-edge region for the stationary flap, the oscillating flaps do not have any effects on the breakdown location. However, when the breakdown location occurs near the trailing edge region for the stationary flap, the effect of the oscillating flaps is greatest. The experiment conducted by Q. Deng and I. Gursul is relevant because it provides some facts about how oscillation flaps can affect the vortices. The flow downstream of the vortex breakdown is unsteady, which affects the stability of the aircraft. Vortex analysis needs to be researched to better understand the theory behind oscillating flaps.

In the case of a swept wing, rather than a basically two-dimensional wing discussed above, the focus of surface oscillation would be to delay vortex breakdown and
maintain highly concentrated and stable leading-edge vortices. From Yao’s vortex tube experiment, the spiral wave can delay bubble-type breakdown. [12] Also, the spiral wave can change the breakdown from bubble type to spiral type, where spiral types always occur further downstream than the bubble types, thus delaying the breakdown. [12]

Many experiments have been done that proves the effectiveness surface oscillation had on providing high lift coefficient at high angle of attack. The hypothesis is that using oscillating leading and trailing-edge flaps increases lift coefficient for aircraft that fly at a high angle of attack.
3.0 Model and Actuator Design

In constructing the model, an inquiry was first made into the most recent model to see which component would and would not work for the requirements given. The current model is only capable of driving the leading edge flaps, but both the trailing edge flap and the leading edge flap must be able to oscillate in order to have successful wind tunnel testing in order to establish that the oscillating flaps can increase lift. At this point, past designs were researched to locate any form of actuator systems that could possibly work with this model. The two systems that appeared to be feasible were a hydraulic system and an electromechanical system, but as neither system was suited to the current needs, a new actuation system was designed.

3.1 Hydraulic Actuator Systems

Past groups have used hydraulics on this project’s actuation system for many reasons, often being because Dr. Stearman kept such a system available for use. In the past, this unit has been used in many projects including driving the F-111 wing. Another benefit of the system is that the hydraulic unit’s response is fast enough to oscillate the model’s flaps at the required frequency to accomplish the projects goals. In addition to convenience and a speedy response, the system was more than powerful enough to drive the control surfaces that needed to be oscillated [3].
3.1.1 How Does Hydraulics Work?

The main principle behind hydraulics lies in the concept that if you apply a force to an incompressible fluid, that force will then be transmitted throughout the fluid and will be applied to every surface with which it comes into contact. Thus, if a 100 lb force is applied on a piston an equal 100 lb force will be transmitted to the piston on the other side, as shown below.

![Distribution of force in an incompressible fluid][17]

Equally in importance is the concept of hydraulic multiplication, occurring when the size of the pistons are varied. Implementing this size change alters the relationship between the input force and the output force. For example, as illustrated below, the piston on the right has nine times the area of the piston on the left. This is can be seen from the equation:

\[ P = \frac{F}{A} \]  

Eq. 3.1

---

[17]: https://example.com/image.png
Because the pressure is due to the input force, it remains a constant. When area is increased, as shown in the equation, it is multiplied directly times the pressure showing an increase in the force. Therefore, as shown, the piston with nine times the area then also has a force nine times greater than the input force.

![Hydraulic Multiplication](image)

**Figure 3.2:** Example of hydraulic multiplication [17]

In this example, however, a drawback is that the smaller piston must move further than the larger piston, while the amount of work of each piston is equal. Most hydraulic systems, including those in tractors, aircraft, and other common pieces of heavy duty equipment take advantage of the possible multiplication factor by including a high pressure pump to push against a small piston, which then allows for large forces to be created, similar to the example as seen above [17].

### 3.1.2 Reasons For Not Using Hydraulic Actuation Systems

Although hydraulic systems have many advantages and are commonly used in many systems, there are a number of drawbacks. Namely, they are very complex. In one
system, many parts are required including hoses, pumps, fluid, pistons and a power source. The system provided to ATAK Technologies by Dr. Stearman was heavy and awkward to maneuver. This would have complicated movement of the system to the wind tunnel, as well as the setting up process needed for wind tunnel testing. In addition, the hydraulic systems require maintenance; the pumps and filters of the system become dirty over time and thus breakdown occurs. This creates a problem because the members of ATAK have never performed maintenance on a hydraulic system. Most importantly, however, is the fact that the hydraulic system provided to ATAK did not have an adequate power source. Repairing the provided power source would have been too great an expense, exceeding the available budget of ATAK Technologies. All of the above reasons led to the decision of abandoning the use of hydraulics as a form of actuator by ATAK Technologies [3].

3.2 Electromechanical Actuation Systems

Active Wing Engineering (AWE) was the last team to work on this project and settled on a form of actuation system known as electromechanical actuation. There are a variety of electromechanical actuators, including piezoelectric and memory metals; however, for the AWE project it was determined that an electric motor would be the best way to drive the flaps. There are three clear benefits associated with using an electric motor as the actuation system, one of which is size. The whole system is much smaller than the hydraulic system, making it easier to move around. Secondly, there is no
required maintenance on this type of system. The most important benefit, however, is the cost. The entire electric actuation system was provided by Dr. Stearman at no cost.

3.2.1 How Do They Work?

Whereas a hydraulic system requires a high pressure pump, fluid, and tubing to drive the flaps, the design AWE created needed only an electric motor and a motor controller. An electric motor works by using natural repellent and the attractive forces of magnets. On one side of the motor rests the north pole of the magnet and on the other side the south pole; while the middle segment of the motor is an electromagnet.

![Coils and brushes inside motor](image)

**Figure 3.3:** Coils and brushes inside motor [17]

When a current is applied to the motor, the inside coil becomes magnetized and repels itself away from the nearby magnets. After the shaft rotates 180 degrees, the brushes then reverse the current and the shaft is pushed around another 180 degrees in the same direction, where the cycle will then repeat itself [17].
In the AWE project, the motor had a circular disk mounted to the end of the motor. The disk was then attached to a shaft, which in turn was connected to another shaft at a right angle. Finally, a third shaft was attached to the flaps, and connected to the setup. This system can be seen in the following figures.
When the motor was turned on, it would drive the first shaft back and forth, similar to a connecting rod in an automobile engine. The back and forth action of this rod coupled with the movements of the intermediate and final rod caused the flaps to oscillate back and forth at the same frequency as the motor. The figure below shows the flap set up in greater detail.
3.2.2 Reasons for Abandoning this System

There were many drawbacks associated with using this system. The size of the system, although much smaller than the hydraulic system, was still quite large. This would make moving the model from the lab to the wind tunnel for testing more difficult. In addition, the model was not designed with the wind tunnel in mind, and it could not be mounted in such a manner as to allow coefficient of lift and coefficient of drag data to be determined. More importantly the controller used to drive the motor is very complex, as shown in Figure 3.8.
3.3 The ATAK Design

After carefully reviewing all of the research of the previous teams, ATAK Technologies has decided that the actuation systems already designed would not be adequate in driving both the leading and trailing edge flaps. ATAK then spent time brainstorming and decided on experimenting with a new design. This design is an improvement on the electromechanical design that Active Wing Technologies had
previously developed. These changes will allow for all the necessary measurements to occur in order to obtain good wind tunnel testing data.

One of the main improvements with this design is that the control system is much smaller than that of any other design, so small in fact, that the new motor will be capable of being mounted to the spar of the wing. This improvement will make moving the model for testing easier. Furthermore, the size constraints and sting attachments of the wind tunnel were taken into consideration when designing the new model, whereas they were previously disregarded. This will ensure that the new model will be capable of being used in the wind tunnel so that it may obtain aerodynamic testing data. The design also allows for a much greater flexibility in testing. The frequency of oscillation, angle of deflection, and even the phase between leading and trailing edge flaps can all be controlled in this design, ensuring that the model will be able to do what is required of it in order to obtain pertinent data. And perhaps most importantly, the model will be very easy to operate. Instead of having to understand a very complex controller, ATAK Technologies will only need to read the digital display of a handheld tachometer to obtain the frequency at which the system operates.

3.3.1 How Will the Design Work?

The design ATAK Technologies has created incorporates the information accumulated by past projects, while developing a new design with several different features. The system designed by ATAK Technologies will utilize a small electric motor provided at no additional cost by Dr. Stearman. The forces involved in oscillating the
leading and trailing edge flaps are small enough that an electric motor is powerful enough for this application. The proposed design of the model is shown in figure 3.9 below.

![Overall Model Assembly](image)

**Figure 3.9: Overall Model Assembly**

In the picture it is apparent that one main spar is supporting the entire structure; this metal spar will be machined and constructed in the basement shop of the WRW building. The use of metal as opposed to balsa wood will ensure the durability of the model during testing, as well as guarantee the resilience of the model for many years so that it might be accessible to future groups. Also seen in the image are the ribs and trailing and leading edge flaps; the angle of this image does not provide for a clear picture of the motor and actuation device, therefore one is provided below in figure 3.10.
In this figure the underside of the main spar is visible; the motor is clearly shown, as well as the drive shaft that attaches to it. This shaft is supported by aluminum guides, keeping it in place. The highlighted region has been enlarged in the following figure (3.11) to obtain a clearer picture of the gearing mechanism that drives the actuation system.
The shaft on the left is connected to the motor on one end, and on the other, it is attached to a bevel gear, which then connects with the bevel gear of the vertical shaft. These bevel gears change the rotation of the horizontal shaft into a vertical rotation. On the right side of the vertical shaft is a third bevel gear which is attached to another horizontal rod. This gear assembly allows for a transfer of the rotational motion back to the horizontal axis. The rod then travels to a second assembly identical to the one described. Since these assemblies are connected they allow for both the leading and trailing edge flaps to rotate at the same frequency.

The actuation system referred to above is somewhat complex requiring more description as well. The purpose of the actuation system is to change the rotational motion input by the vertical shaft into the translation motion needed to drive both flaps. A close up image of the slider-crank assembly is shown in the next figure (3.12).
As the blue control wheel rotates, it pulls the connecting rod attached to it in a back and forth motion similar to the internal action of a crankshaft in an automobile engine. The blue slider attached to the connecting rod is also pulled in a back and forth motion, but it is not allowed to rotate due to the silver block which keeps its motion restricted to one axis. The blue slider in the design is actually a push rod similar to those commonly used in radio controlled aircraft. The entire system, including the push rod, is shown below in figure 3.13.
In this figure, the control wheels are blue as in previous figures, but the pushrod is illustrated in red. The pushrods connect to the control horns shown in the image; the purpose of the control horn is to use the translational motion of the pushrod to rotate the control surface about its hinge axis. In this case the control surface to be moved is the leading edge slats and the trailing edge flaps. It accomplishes this rotation by imparting a moment on the control surface. A detailed illustration of the control horn is shown below in figure 3.14.
Similar to the above figures, the red rod in this figure is the push rod. It connects to the control horn via the clevis which is illustrated in silver. The clevis allows the control horn to rotate as it pushes it back and forth. Since the control horn will be attached to the leading and trailing edge flaps and the control horn will rotate, the flaps will be forced to rotate as well. To better visualize the whole system, the spar, actuation system, push rod, control horn, and flaps are all shown in the next figure (3.15).
In this figure, the push rod that runs to the right is connected to the leading edge flap, while the other push rod is connected to the trailing edge flap. A side view of the system best visualizes how the push rod and control horn cause the flaps to rotate, this view is illustrated below in figure 3.16
This figure (3.16) shows an interior side view of the model highlighting the push rods from the main spar all the way to the edge of the flaps. The model is therefore able to oscillate both the leading and trailing edge flaps. Varying the parameters during this is extremely simple. To change the frequency of oscillation, simply increase the amount of power to the motor and record the frequency with the tachometer. The amount of deflection can be controlled by changing where the slider connects to the control horn. Finally, the phase can be controlled by connecting the slider assembly for the trailing edge flaps at a different position in the cycle from the leading edge flaps. A figure showing the model with no deflection of the flaps (3.17) and a figure showing the flaps deflected 15 degrees (3.18) is illustrated below.

![Figure 3.17: Wing Model Without Deflected Control Surfaces](image1)

![Figure 3.18: Wing Model With Deflected Control Surfaces](image2)

It can be observed that a small part of the slider and the control horn will be in the free stream, but this will not significantly increase the drag, or decrease the lift. This is
due to the fact that the elements in the free stream are very small as compared to the overall wing model.

In order to know at what frequency the flaps are operating, the shaft on the side of the model opposite the motor will be connected to a propeller. As the propeller spins, a handheld tachometer used for radio controlled models will measure the speed at which the propeller rotates. This will greatly simplify the task of determining the frequency; an example of a handheld tachometer is shown in figure 3.19 below.

![Handheld tachometer](http://www.rchelicopters.org)

**Figure 3.19:** Handheld tachometer [http://www.rchelicopters.org]
4.0 Recommended Model Testing

With a wind tunnel model developed and ready for modifications, the next step in the growth of the active aeroelastic wing project is to carry out tests in the wind tunnel in accordance with project guidelines. ATAK Technologies’ model has been designed to be used in the wind tunnel located in room 2 in the basement of W.R. Woolrich Laboratories.

The purpose of this section is to provide future teams with information on the type of testing that should be done, along with explanations of how those tests can be carried out. In these tests, data is to be recorded and reduced in order to study the effects of the active aeroelastic wing. It is with these tests and this data that future teams will be able to make advancements on this project.

4.1 Testing Theory

Model testing is based in the laws of similarity. In order to have complete similarity between model and full size structures this similarity must be geometric, kinematic, and dynamic [18]. To have kinematic similarities, there must be a constant ratio between the two sets of data. This is to say that there must be a direct ratio between the two sets of corresponding velocities. For dynamic similarities there must be a constant ratio between the corresponding sets of forces. The investigation of these ratios should not be too complicated. This project is intended to model an F/A-18 wing. By obtaining the size of true size F/A-18 wings and by using previous knowledge of aerodynamic and atmospheric forces, one should be able to calculate the ratios with little difficulty. Due to the complexity of the design of the F/A-18, and the fact that military
airplane designs are not readily available, the constructed model is not totally similar to that of the F/A-18. However, the concepts used and the theory behind the construction and testing are strong enough to provide the critical data to validate the project’s goals.

There is a specific method of testing that should be followed in order to ensure that all processes are carried out effectively. The following diagram (figure 4.1) provides a layout of this method.

**Figure 4.1: Modeling and Testing Procedures**

ATAK Technologies has completed 1, 2 (a and b), 3a and 4a. With these steps already completed, the next team should be able to go directly into modifying the model in any way necessary to comply with the testing procedures. After this is finished they will be able to actively test the model in the wind tunnel.
4.2 Testing Goals

When taking on a project such as this one it is important to set out clear goals in the beginning. This will be very important for the testing procedures. ATAK Technologies has developed three main goals that should be focused on in the early stages of testing. The goals are as follows.

4.2.1 Work to Advance the Project

The active wing project is ready to be taken to the next level. The team that follows ATAK Tech will have the power to take the project development to the next level. This can be done by beginning work on the model immediately following the start of the semester. It will be imperative to set out a schedule for the first few weeks of the semester and to follow it closely. Immediate progress is a must in order to gain the momentum needed to accomplish a great deal of work done throughout the semester. If these objectives are obtained, the later groups should have no trouble in achieving their goals.

4.2.2 Obtain and Reduce Data:

The key to making true progress on this project is to obtain and reduce data. The acquired data can then be compared to previous research done by outside parties. There has been a great deal of research done on this type of project at other institutions and if the next group makes the right contacts, some useful reports may be obtained. The best way to come across these contacts is to make an inquiry to Dr. Stearman. Dr. Stearman should
be able to put the group in contact with the necessary people, or at least point the group in the right direction.

4.2.3 Conduct Repeated Tests:

It is to be assumed that the next team will have limited experience in wind tunnel testing. It is for this reason that ATAK Tech recommends that each wind tunnel test is practiced and repeated several times to ensure that accurate reliable data is acquired. The best way to successfully complete wind tunnel test is to practice and to be totally familiar with the testing procedures. It is recommended that the group find a knowledgeable advisor to assist in the early testing stages.

By concentrating on these objectives, and making them the primary goals for the first part of the semester, ATAK Tech feels that a great deal of good will come from the work accomplished.

4.3 Data Acquisition

There are four relationships that should be focused on when testing the model. Those that ATAK Technologies have taken to be the most important are the relationships between oscillation frequency and:

- Coefficient of lift variations
- Pressure distribution over wing
- Wing spar strain
- Wing tip flutter
The configurations of the wing model in the wind tunnel can be easily altered. This ability will allow for many different testing scenarios. The angle of attack can be changed as many times as necessary. At each desired angle of attack the leading and trailing edge flaps can be oscillated at different frequencies. By doing this and also by varying the wind speed it will be possible to gather data from many types of flight conditions, allowing for a wider range of data acquisition. With the data taken it should be possible to observe the oscillation frequencies that will optimize the relationships mentioned above. The optimized values will be very important when making conclusions. One will want to find the frequency at which the maximum amount of lift is produced. Likewise, the frequencies for which the strain on the wing spar strain and wing tip flutter are minimized are vitally important.

4.4 Instrumentation

The following section is to introduce some of the instrumentation that ATAK Technologies feels would be best suited to accomplish the goals of this project. ATAK Technologies makes these suggestions with the hopes that future teams will be able to use them, but also strongly encourages further investigation of testing processes and testing options in the future.

4.4.1 Visualization

Visualization will be a key factor in the understanding of the physical occurrences while testing. When studying the flow over an airfoil one of the best methods of visualization is the introduction of smoke into the airflow. This is easily done with a smoke wire,
which is currently set up in the ASE wind tunnel. One of the benefits of leading edge flaps is the fact that they help the flow re-attach on the wing, which causes higher lift. This can be observed with the smoke in the air flow. First one would observe the wind flow with zero deflection of the flaps, then with the flaps at an angle, or even with the flaps actively oscillating. The smoke produced will have approximately the same density of the air in the flow; therefore it will travel very well along the stream. This will provide a clear, visible flow field around the model. Due to the fact that smoke dispersion and condensation increases with velocity these tests will be limited to low speeds though [18].

4.4.2 Model Modification

It will be necessary for the next project group to modify the ATAK Technologies wing model. One of the main changes that will be made is the addition of pressure taps on the surface of the wing. Figure 4.2 shows logical locations for these taps. It is important to place the taps in positions that will allow for proper computer modeling. By placing them in parallel sections along the wing, it will be possible to make a clear plot of how the pressure distribution varies. This will be done in order to take pressure measurements over the wing in different configurations. Having the pressure distribution over the wing allows for the analysis of the flow behavior over the wing with different flap oscillatory frequencies. The wing can be digitally modeled and a plot of the pressure distribution can be made. Seeing a physical representation of the tests is a good way to help understand exactly what changes occur when the configuration of the wing is altered.
Strain gauges should also be added to the spar of the wing model. Placement locations can be seen in figure 4.3. This should be done in order to test the structural stability of the wing under strained conditions. With the wind tunnel at its higher speeds and the flaps oscillating at a rapid frequency it is entirely possible for the wing to be subjected to moderate level forces that could cause damage to the spar. Adding strain gauges can be a very tedious and time consuming task. There are many steps that must be taken to ensure that the gauges are attached properly. As recommended with the initial tunnel testing, it
would be a good idea for the group to seek out an advisor when working on the strain gauge attachment process.

Another simple addition to the wing model will be that of an accelerometer to the end of the wing to test for levels of wing flutter (figure 4.33). Flutter is an unwanted occurrence and should be avoided at all costs. As with the strain on the wing spar, flutter can occur when the wing is subjected to high stress levels. Flutter can also come from the right combination of airspeed and flap oscillation frequency. The accelerometer will allow for the observation of the vibrations which can be then analyzed, and in turn, adjustments can be made to the testing configuration.

**4.5 Summary of Testing Suggestions**

In conclusion, ATAK Technologies has three main suggestions it makes to future groups:

1) Modify the active wing model design as needed

2) Begin testing as soon as possible
3) Understand theory behind data acquisition and the equations needed to reduce the data.

With these three things in mind, ATAK Tech feel that the next project group will have all tools necessary to take this project into the next stage of development.
5.0 Progress Report

ATAK Technologies has spent the first half of the semester by and large in the planning and development stages. Theory research has been carried out in order to better understand the scope of the task at hand. The following section will outline the work completed and work pending. Also included is a discussion of work that was mentioned in the preliminary presentation that will no longer be included. A detailed schedule of the rest of the semester’s work will be displayed as well.

5.1 Work Completed

Over the past semester, ATAK Technologies has successfully performed literature research on the benefits that an active wing could provide in modern aircraft design. This research included the different tools that will be used to operate and test the wind tunnel wing model. The possible actuator systems were studied; these systems included hydraulic and electromechanical actuators. Also, the measurements tools to be used in the wind tunnel test were studied as well; in addition, information was gathered from the reports of the active wing design teams of previous semesters. This research has been carried out primarily on the World Wide Web, however additional research has been acquired from an engineering library. In addition, much information was gathered from the reports of active wing design teams from previous semesters. In the course of this research, the team has garnered an understanding of active wing theory and technology to carry out the design and development of the wind tunnel model. Team members produced an AutoCAD design of the wing model spar which will be passed along to the
Department of Aerospace Engineering machine shop for fabrication. The design incorporated the mechanical system that will drive the control surfaces on the wing. The remaining materials necessary for the construction of the wing model have also been researched and purchased. These components of the wing model have been prepared for insertion into the wing spar model. In addition to the research and design work done, much care has been taken in the preparation of WRW 316, the Active Wing Laboratory, for the construction and development of the wing model. All the completed activities and pursuits of ATAK Technologies can be shown in Appendix D.

5.2 **Recommended Future Work**

This section presents recommendations that ATAK Technologies has made to future groups associated with the active wing project. It has been broken down into sections based on the work recommended for *completion of the construction of the wing model*, *wind tunnel testing*, *research*, and *data reduction*.

5.2.1 **Complete Construction of Wing Model**

The complete set of drawings set has already been produced by ATAK Technologies. Currently, work must be done on the design of the control surface driving system. Also, construction of the wing model is nearly complete. However, some work is still needed in order to fully complete the wing model. At first, it should be the next group’s priority to position all testing equipment on the wing model itself. This means attaching strain gages, accelerometers, and pressure taps. Recommended positions for the measuring equipment is located in the Recommended Model Testing section. After
the testing equipment has been installed, the wing model skin will need to be placed on the model itself. Once this is completed, the complete model can be mounted on a sting and prepared for testing in the wing tunnel located in the basement of the Aerospace building.

5.2.2 Wind Tunnel Testing

As soon as the wind tunnel wing model is completed, the wind tunnel testing will proceed. The steps to be taken in order to prepare for this testing are: research of testing procedure, investigation of wind tunnel capabilities, construction of testing materials (if needed) and wing model preparation. There are steps that must be taken in order to prepare for this testing. Once the model has been fitted with any equipment necessary to acquire data the group must become familiar with the software used to capture data from the model. The equipment fittings will be designed along with the wing model, and then it will be attached following the construction of the wing. Also, the data acquisition system and software will be studied and familiarized before testing begins. When testing begins the data will be recorded and reduced as the testing is furthered. Preliminary tests must be carried out to insure that the wing model will stand up to the stresses of testing and that all incorporated measuring devices are necessary and proper.

Another major part of the wind tunnel testing is the scenarios for which the model will be tested. There are limitless possibilities in testing, so future group must narrow the scope of the procedures. Though the procedure is yet to be determined, current ideas are to first test at a fairly low speed, as if to simulate a landing situation. It must be remembered that the testing tools are only accurate in a specific range of airspeeds, so
that must be taken into account. At the low speeds the angle of attack will be varied as to look at different landing approaches. The same test could be done at higher speeds as well. Ideally, test will be run at three airspeeds: low, intermediate and moderately high. The intermediate airspeed level would enable the team to test a low angle gliding flight scenario, and the high airspeed would represent a sustained high thrust run. Each of these scenarios are important in the area of active wing technologies, as well be described in the final report. The same will be true for the angle of attack. The final determination of testing procedures will be made during construction of the wing model.

5.2.3 Research

Though research has already been carried out, more is still necessary. There needs to be research on the testing procedures that will be pertinent to future project objectives and wind tunnel test history, along with extended investigation of the benefits and usage of active wing technology. As mentioned earlier in the report, ATAK Technologies has not made a decision on the exact wind tunnel measuring system equipment to be used. This is another issue that is necessary to discuss with the project sponsors and other various experts. The exact workings of these measuring tools must be better understood to make an educated decision; therefore extensive research must be done on this subject as well. Also, additional research will be carried out which regards to the benefits of active smart control surfaces on aircraft wings. The final subject that must be researched is the benefits of active wing technology over other current flight capability enhancing devices, such as the vertical flight fan used in the joint strike fighter (JSF) being constructed by the Lockheed Martin Corporation.
5.2.4 Data Reduction

Once the data from wind tunnel testing has been completed, the active wing project is not over. The collected data needs to be reduced, or interpreted, into a more useful form of data. This can be done using several different techniques, all at the discretion of the group reducing the data. ATAK Technologies recommends showing the relationship between the desired elements, such as the coefficient of lift, and the frequency at which the flaps are oscillating. These relationships can be transferred into graphical form in order to aid comprehension of the collected data.
6.0 Cost Analysis

ATAK Technologies minimized the cost of the active wing project. With this objective in mind, ATAK to utilized existing equipment previously obtained by the Aerospace Department or previous groups. The materials required to build the active wing model were provided by the Department of Aerospace Engineering machine shop and bought from an appropriate materials provider. The wing spar as described in the Model and Actuator Design section, with materials gathered without cost from the Aerospace Department, was constructed through use the departmental machine shop. The electromechanical motor used to oscillate the control surfaces of the wing is currently in the possession of ATAK Technologies.

The remaining materials required for the construction of the model were acquired using funding provided by the Department of Aerospace Engineering. The bevel gears used in the model’s actuation system were acquired from www.ehobbies.com, an internet provider of mechanical gears. The other materials, such as the balsa wood and push-pull rods, were found at www.towerhobbies.com, an online hobby store. The equipment used to facilitate the construction of the model was provided by ATAK Technologies. A total expense report for ATAK Technologies participation in the active wing project, is shown in Figure 6.1, as well as included in Appendix B of the ATAK Technologies final report.

To aid future groups’ participation in the active wing project, additional equipment required for model testing was located. The equipment necessary for measurement of the airflow within the wind tunnel will be provided by the Department of
Aerospace Engineering (ASE). The sting, which will be used to measure the lifting effect of the active wing, will also be provided by the ASE Department. The tachometer used to calculate the oscillation frequency will be provided by the Design Build Fly (DBF) organization. There were no unforeseen expenses concerning the activities of ATAK Technologies. Our expenditures were well within the limit set by the Department of Aerospace Engineering.

<table>
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<th>Item</th>
<th>Cost</th>
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<tbody>
<tr>
<td>Top Flite MonoKote Blue Mist 6'</td>
<td>$10.99</td>
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<tr>
<td>Dubro Heavy Duty Control Horn System (2)</td>
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<tr>
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<td>$36.00</td>
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<tr>
<td><strong>Total Cost</strong></td>
<td><strong>$90.08</strong></td>
</tr>
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Figure 6.1: Illustrated Materials Expense Chart
7.0 Conclusions

Active aeroelastic wing research is important in the progress of contemporary aircraft design. ATAK Technologies is proud to be included in the development of this technology. This report marks the completion of the time allotted for the completion of ATAK’s project objectives. While we did not accomplish all of the objectives initially stated at the beginning of our participation in the development of an active wing model, the most important objective for this semester was completed. Even though much work needed to be completed, ATAK Technologies was able to fully design and develop a functional active wing model to be used by future engineering teams. Other goals initially proposed, but eventually discarded include the testing of the structural tolerances of the model as well as begin preliminary testing of the model. Recommendations have been made in order for future groups to best utilize the design of the ATAK Technologies model. Hopefully, the progress achieved by ATAK Technologies will be used for future research in active aeroelastic wing design.
8.0 References


   http://adg.stanford.edu/aa241/AircraftDesign.html


Structure Design.” British Hydromechanics Research Association, Bedford,  

http://www.efunda.com/designstandards/sensors/sensors_home/sensors_home.cf  
m. (4 March 2003.)

80-82, 91-93.
Appendix A: Expanded Model AutoCAD Views

After the receipt of this final report by Dr. R. O. Stearman, an additional amount of material will be submitted at a later date. This material will include the physical wing model, as far as ATAK Technologies has constructed it, as well as detailed AutoCAD drawings of the wing model. These highly expanded views will contain dimensions of the wing components, such as the actuation system, wing spar, and rib sections. The following four magnified views are included in order to aid in the
Figure A.1: Expanded Diagonal View of Wing Model
Figure A.2: Expanded Top View of Wing Model
Figure A.3: Expanded Side View of Wing Model
Figure A.3: Expanded Rear View of Wing Model
## Appendix B: Materials Expense Description

<table>
<thead>
<tr>
<th>Item</th>
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</table>

*Figure B.1: Illustrated Materials Expense Chart*
Appendix C: Proposed Measuring Equipment

The testing procedures that will be carried out in the wind tunnel tests are currently under investigation. ATAK Technologies wishes to study the lift characteristics of the wing model by taking measurements of the physical properties of the wing coupled with the static and dynamic air flow properties around the wing. There are currently two prospective flow-measuring methods under investigation: pitot tube and hot-wire anemometry. The following section will discuss the theory and mechanics of both methods, and their relation to the analysis of lift characteristics.

C.1 Pitot Static Tube Theory

Figure C.1: Classic Pitot Static Tube [19]
Pitot tubes are used as speedometers for aircraft. The Pitot tube measures the fluid velocity by converting the kinetic energy of the flow into potential energy. This conversion takes place at the stagnation point, located at the Pitot tube entrance [19], as seen in Figure C.1. At the stagnation point, the tube takes the measurement of the stagnation pressure, and the static taps on the outer layer of the tube measure the free-stream pressure. The pressure transducer then takes the difference between the two measurements. Using Bernoulli’s equation (Eq. C.1), this value is then used to calculate the velocity of the flow.

\[ P + \frac{1}{2} \rho v^2 = \text{constant} \quad \text{Eq. C.1} \]

\( C_L \) can be found using the following equation.

\[ C_L = \frac{2L}{\rho v^2} \quad \text{Eq. C.2} \]

There are two fundamental problems with using Pitot static tubes for flow measurements. The first occurs in low speed flow, where the difference in the two pressure measurements is very low, and there exists a possibility that the error in the equipment could be greater than the actual measurements. Secondly, in supersonic flow, the laws that Bernoulli’s equation are based upon are no longer valid due to the creation of shock waves, which results in a large error in the measurements. “Due to these errors, a true reading of the dynamic pressure within about 0.1% may be obtained [20].”

Located below are some of the fundamental pros and cons of using Pitot static tubes for flow measurements [19].

- **Pros**
• Simple Construction
  o Relatively Inexpensive
  o Little calibration required
  o Introduces little pressure variations in the flow
  o Requires only a few access holes into the flow conduit; no wide open cut needed

• Cons
  o Accuracy may not be high enough for some applications such as very low and very high speeds
  o Tube must be very well aligned with the flow to be accurate (Yaw misalignment not to exceed 5° in either direction)

C.2 Hot Wire Anemometry

![Hot Wire Diagram]

Figure C.2: Classic Hot-Wire Design [19]
The hot-wire is the best known thermal anemometer. It measures flow velocity by noting the temperature change caused by the flow [19]. “A hot-wire anemometer is made up of a small-diameter platinum wire (about 0.015 mm) of short length (about 10 mm) which is placed in the airstream so that its length is perpendicular to the mean airflow direction [20].” A small current is passed across the wire to cause a heating effect. The airflow across the wire will cause fluctuations in temperature, which results in fluctuations in the wire’s resistance. “Fundamentally, the hot-wire anemometer is supposed to indicate the rapidity of the fluctuations by an identical frequency of current change, and the amplitude of the fluctuations by the amount of current change [20].”

As with the Pitot static tube, there are pros and cons associated with hot-wire anemometry.

Some of those pros and cons can be seen below [19].

- **Pros**
  - Very good spatial resolution
  - High frequency response (between 10-400 Hz)

- **Cons**
  - Wire is fragile, can only be used in clean gas flows
  - High cost
  - Calibration need very often, due to dust accumulation

Eq. C.3 below shows the relationship between the temperature drop and electrical power.
\[ I^2 R_w = h \cdot A_w (T_w - T_f) \]  
Eq. C.3

Where \( I \) is the electrical current, \( R \) is the resistance of the wire, \( h \) is the heat transfer coefficient of the wire, \( A_w \) is the cross section of the wire, and \( T_w \) and \( T_f \) are the wire and fluid temperatures respectively. The resistance of the wire is also a function of temperature, as shown in the following equation.

\[ R_w = R_{REF} (1 + \alpha(T_w - T_{REF})) \]  
Eq. C.4

\( R_{REF} \) is the wire resistance at a reference temperature, \( T_{REF} \), and \( \alpha \) is the thermal coefficient of resistance. The heat transfer coefficient is a function of fluid velocity, which is necessary to calculate the pressure.

\[ h = a + b \cdot v_f^5 = \frac{I^2 R_w}{A_w(T_w - T_f)} = \frac{I^2 R_{REF} (1 + \alpha(T_w - T_{REF}))}{A_w(T_w - T_f)} \]  
Eq. C.5

Solving Eq. C.5 for the fluid velocity produces Eq. C.6.

\[ v_f = \left[ \left( \frac{I^2 R_{REF} (1 + \alpha(T_w - T_{REF}))}{A_w(T_w - T_f)} - a \right) \right] \]  
Eq. C.6

Coefficients \( a, b, \) and \( c \) are all values that are obtained from calibration. (Above derivation courtesy of www.efunda.com [19]) With the fluid velocity known, it is possible to calculate the coefficient of lift.
Appendix D: Completed Project Activities and Durations

Figure D.1 Completed Activities and Durations