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SAE Aero Design: Aero Propulsion Team – Designing a R/C Plane Using a 3-Wing Layout with a Canard Capable of Carrying a Payload.

Michenell Louis-Charles, Adrian Moya, Sasindu Pinto, Cameron Riley, & Noah Wright

FAMU-FSU College of Engineering

Abstract

This year's SAE Aero Design Competition required teams to design a R/C plane capable of carrying a cargo load. The team used a canard-main wing-tail stabilizer layout for the plane. The canard wing allows for better lift distribution in the plane compared to a traditional main wing-tail stabilizer layout. However, stabilizing the canard layout required the addition of the tail wing. Theoretical pitch stability calculations were done using MATLAB. Following that, the calculations were initially validated using XFLR and then wind tunnel testing. Wind tunnel tests were conducted for different angles of attack. Based on the finding, it was concluded that the 3-wing layout considered in the paper is a method to create a stable cargo aircraft with a canard wing. Furthermore, the stall angle of attack (AoA) correlates with the expected value from calculations and XFLR numerical simulations.

Introduction

The SAE Aero Design competition is an annual aircraft design competition. The objective is to create a cargo plane that can complete a specified flight path. Teams are encouraged to try innovative design concepts. Only electric motors are allowed for propulsion. The cargo load must consist of a size 5 soccer ball and at least one cargo plate.

As the aero-propulsion team of a two-team project (the other team been the geometric team), we focused on airframe design, stability, and propulsion. 2 different wing layouts were tested during the numerical simulation process, a canard-main wing layout, and a canard-main wing-tail stabilizer layout. Following this, computational fluid design (CFD), both dynamic and numerical, were conducted. Those results were validated using wind tunnel testing.

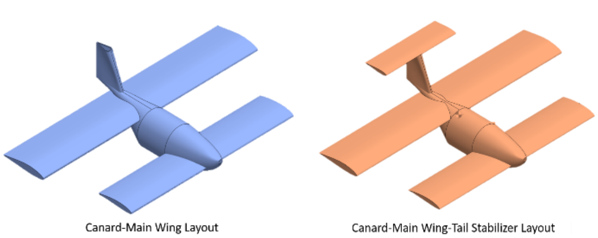


Figure 1: Wing layouts considered.

Motivation

With innovation in mind, we decided to create a canard plane. While canard planes are harder to stabilize, they do distribute the lift produced by the plane more evenly. This also creates a natural feedback loop which improves stability as the canard stalls before other wing(s) on the plane (assuming the other wings do not stall). Furthermore, the canard layout makes it easy to load and unload cargo while keeping the CG position within the required region for a stable flight. The objective is to validate the pitch stability of the plane with a canard layout. This would require theoretical calculations followed by computational simulation and wind tunnel tests.

Disclaimer

All values provided are English units, unless specified otherwise. As the test flight was not completed at the time of writing, it was assumed that the wind tunnel testing and theoretical lift/drag values were correlating with actual performance of the plane. Furthermore, this paper only discussed pitch stability, as roll and yaw stability were not validated before the test flight.

Methods

The following sections breakdown the design procedure for the selected concept. To determine the physical properties of the plane, a computer aided design (CAD) model was created using SolidWorks. Following that, stability calculations were performed while making edits to the CAD model to get desired results. XFLR5 simulation software was used to validate stability. CFD was performed using SolidWorks Fluid Flow Simulation toolbox and results were validated using wind tunnel testing.

Determining Dimensions

To determine physical properties and dimensions of the plane, a CAD model was created and modified using SolidWorks. The following model was created, and physical properties were found.

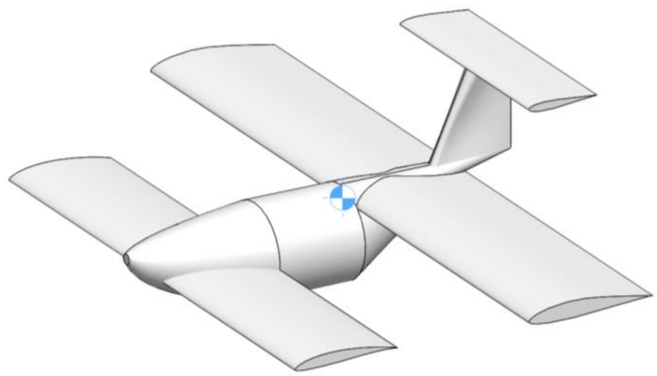


Figure 2: CAD Model

The CG for this model was at 20.5 *inches* from the front of the plane and 1.8 *inches* below the top of the fuselage. The weight of the plane was expected to be 10.5 *pounds* without cargo and 12.5 *pounds* with cargo.

Stability Calculations and Simulation

Stability calculations were done by calculating the coefficient of moment of the center about gravity of the plane, with the main wing as the controlling wing. Initially, the moment was found around the CG.

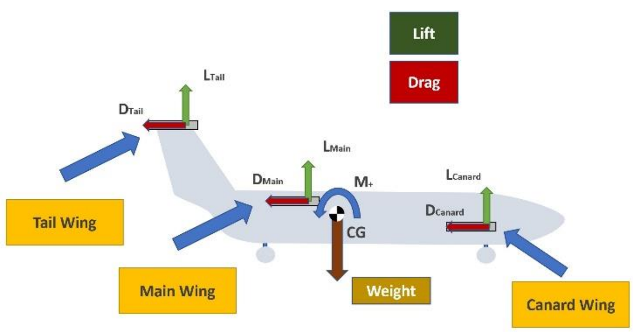


Figure 3: Free body diagram for the plane

The positive moment direction is when the plane creates a positive takeoff angle with the horizontal, which is the counter-clockwise direction in the figure 2. The following equation was derived from the above free body diagram [1].

$$
\begin{aligned}
M_{CG} = L_c \times x_c + L_c \times \sin(AoA) \times y_c - \mathrm{D_c} * \mathrm{y_c} \\
+ \mathrm{D_c} \sin(\mathrm{AoA}) \times \mathrm{x_c} - \mathrm{L_a} \times \mathrm{x_a} \\
- \mathrm{L_a} \times \mathrm{sinAoA} \times \mathrm{ya} + \mathrm{Da} \times \mathrm{ya} \\
- \mathrm{Da} \times \mathrm{sinAoA} \times \mathrm{xa} - \mathrm{Lt} \times \mathrm{xt} \\
- \mathrm{Lt} \times \mathrm{sinAoA} \times \mathrm{yt} + \mathrm{Dt} \times \mathrm{yt} \\
- \mathrm{Dt} \times \mathrm{sinAoA} \times \mathrm{xt} + \mathrm{MAC} + \quad \mathrm{MAM} \\
+ \mathrm{MAT}
\end{aligned}
\tag{1}
$$

Notice that since the AoA is small, cosine values are equivalent to 1, and sine values are similar to the AoA value. The M_A values are characteristic profile moment values for each wing. C, a, and t refer to the canard, the main wing (aft wing) and the tail wing, respectively. All values are taken from the CG. These only depend on the shape of the airfoil. As the controlling wing is the main wing, this value was divided by the dynamic force of the main wing, which is given by the following equation [1].

$$F_{dynamic} = \frac{1}{2} \times \rho \times \mathrm{V}^2 \times \mathrm{S_{aft}} \times \mathrm{C_{aft}} \tag{2}$$

Here, ρ is the air density, V is the cruising speed, S is the wingspan, and C is the chord length for the main wing. The following equation was used to get the coefficient of moment about the CG [1].

$$C_M = \frac{M_{CG}}{F_{dynamic}} \tag{3}$$

This value was used to determine the pitch stability of the plane. The positions and dimensions were adjusted to get a stable flight, which was determined by plotting the C_M vs. AoA plot using MATLAB. A negative slope with a positive C_M value when AoA is required for a stable flight. This allows for the plane to automatically return to a stable flight if it deviates from its stable AoA. Furthermore, that stable AoA value must be positive, so the plane would travel upright.

Xfoil

Xfoil is a program that uses an airfoil's shape as well as the atmospheric conditions of the flight to analyze performance. Using 200 points around the airfoil, the program can create a multitude of graphs to determine how the wing would react under different circumstances. Pictured is all there Eppler airfoils used on this design.

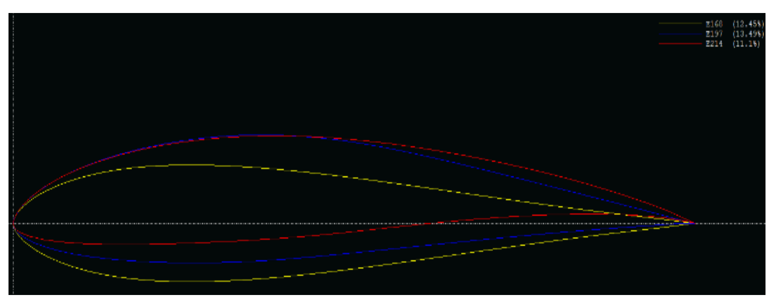


Figure 4: Xfoil wing diagram

The XFLR5 program uses Xfoil analysis of airfoils to predict how a plane will perform. It allows the user to define the plane's shape and assign the wings airfoils. Here is the plane's model depicted in the program.

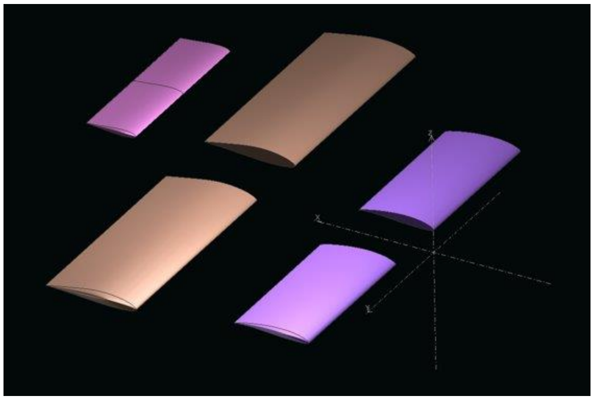


Figure 5: Wing Layout in XFLR5

Data Collection and Analysis

<u>CFD</u>

Parameter	Value
Parameter Definition	User Defined
Thermodynamic Parameters	
Parameters	Pressure, temperature
Pressure	14.6959473 lbf/in^2
Temperature	68.09 °F
Velocity Parameters	
Parameter	Velocity
Defined by	3D Vector
Velocity in X direction	0 in/s
Velocity in Y direction	0 in/s
Velocity in Z direction	-440 in/s
Turbulence Parameters	

Figure 6: Flow simulation settings

CFD was performed using the flow simulation toolbox in SolidWorks. To simulate this, the model was put to have a wind velocity of -440 in/s (about 25 mph, which is the plane takeoff speed) going toward the nose of the plane. To simulate the plane with varying AoA some trigonometry calculations were done to vary the vector of wind speeds that would be affecting the plane in the angle needed. After refining the mesh as much as possible and running the program cut plots were made to visualize the airflow and view the vorticity and turbulence around the fuselage and the wing profiles.

<u>Wind Tunnel Testing</u>

The addition of the canard wing into our design brings along other challenges. The main concern is that the flow over the main wings may be detached from the wing due to the wakes from the canards. To get a live visual of the flow, wind tunnel testing was performed on a model that is proportional in size to our actual RC plane. Another reason behind the testing was to also validate the quantitative data that we got from the CFD.

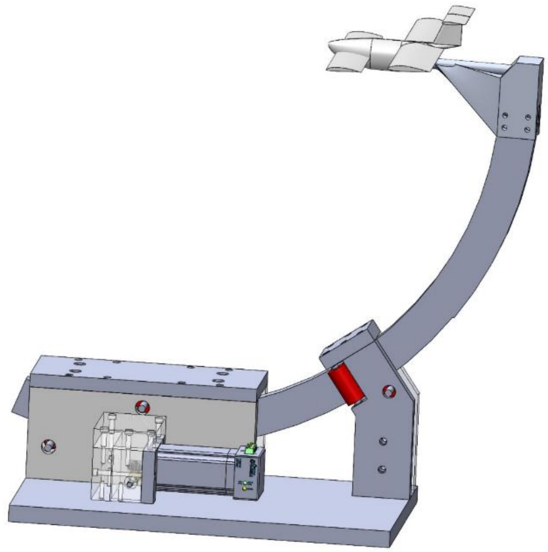


Figure 7: Wind Tunnel Attachment with the model designed by the team.

The plane is mounted in an arc arm to gather data at different angles of attack. Three angles were tested in this experiment. 0 degrees to visualize what the flow would look like during flight. 5 degrees, our take off angle, to replicate take off conditions. Lastly 12 degrees was done to show what the flow would look like once the canards and the main wing has stalled.

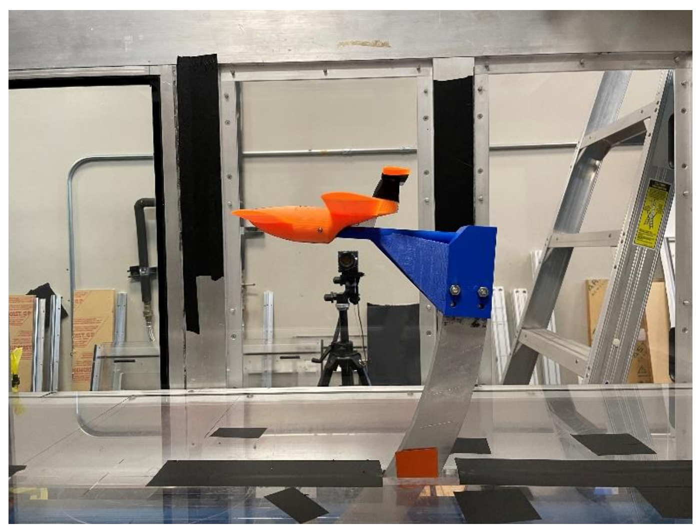


Figure 8: The plane attached to the wind tunnel.

Smoke tests were performed on the model plane. This technique consists of seeding the air with smoke, then turning on the wind tunnel. Once the seeded air is flowing through the wind tunnel, a laser sheet will be used to illuminate the seeded particles in the test section. A high speed MOS camera was utilized to capture the flow as it was going over the model. These tests were performed at the Florida Center for Advanced Aero-Propulsion.

Figure 9: FCAAP subsonic wind tunnel

Smoke images were taken for three angles of attack, zero degree, which would be the AoA for the plane when it's on the ground, 5-*degree* AoA, which will be the takeoff AoA, and 12-*degree* AoA, where the plane is expected to stall. The wind tunnel was operated, and the data were processed by a graduate student work working at the FCAAP.

Results and Discussion

Stability

Using the equations 1, 2 and 3, stability plots were generated. Initially, the canard-main wing layout was used. The following stability plot was generated for the 2-wing layout.

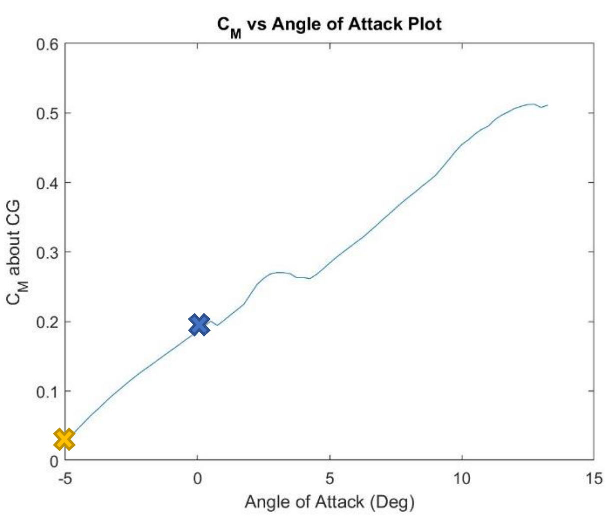


Figure 10: Stability plot for the 2-wing layout

Based on the requirements mentioned in the methods section, this configuration does not provide a stable flight. As shown by the blue X, the C_M value is positive when AoA is zero. However, as shown by the yellow X, the AoA is a negative value when C_M equals zero. This means the plane will not fly upright. As this produces a negative slope, the plane will not return to a stable flight after leaving its stable angle. To fix this instability, the canard-main wing-tail stabilizer layout was considered.

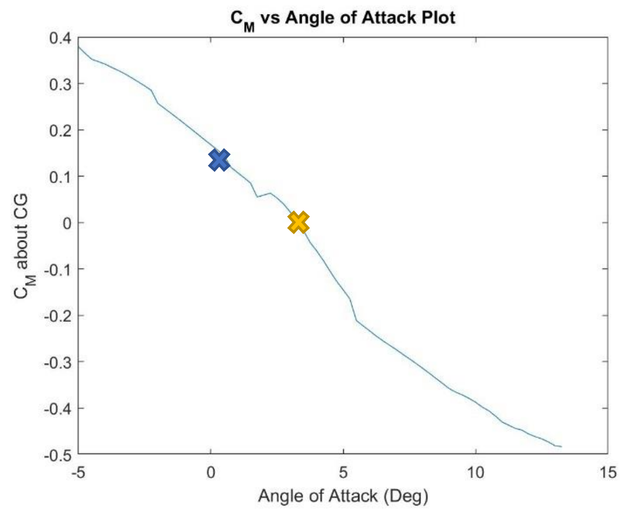


Figure 11: Stability plot for the 3-wing layout

Similar to the initial plot, this also has a positive C_M value when the AoA is zero. However, the AoA value is also positive when the C_M is zero. Hence, we get a positive plot. Not only is the plane flying at a positive AoA, meaning it is upright, but the plane also returns to stable flight automatically when it is not stable. Following this, XFLR was used to simulate the results.

XFoil

An Xfoil analysis was conducted on the selected airfoils to validate their usage on the plane.

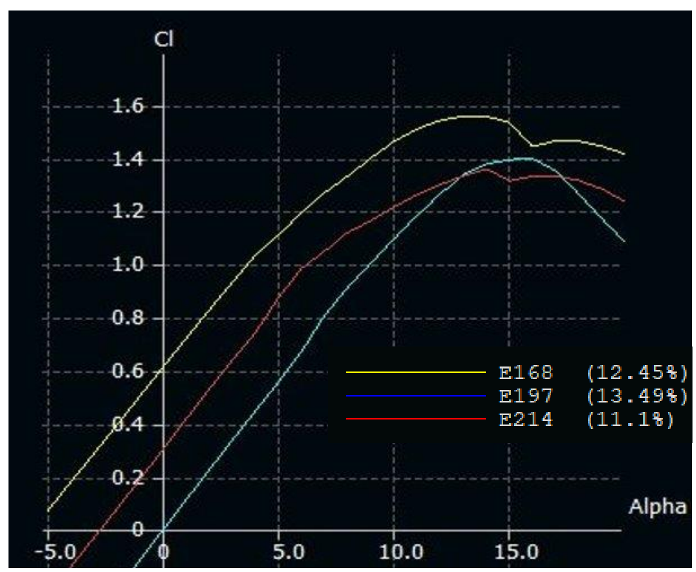


Figure 12: Coefficient of Lift plots from XFLR5

The yellow line represents the canard that peaks first. This represents a smaller stall AoA than the red line representing the main wing. This is essential to the design so the main wing can stabilize the plane in event of a stall.

XFLR5

After analyzing the Eppler airfoils a model of the plane was designed. A C_m vs. AoA plot produced by the experiment shows that the plane will be stable, as indicated by the negative slope. However, it says that the Equilibrium AoA is 10 degrees, far higher than the calculations showed.

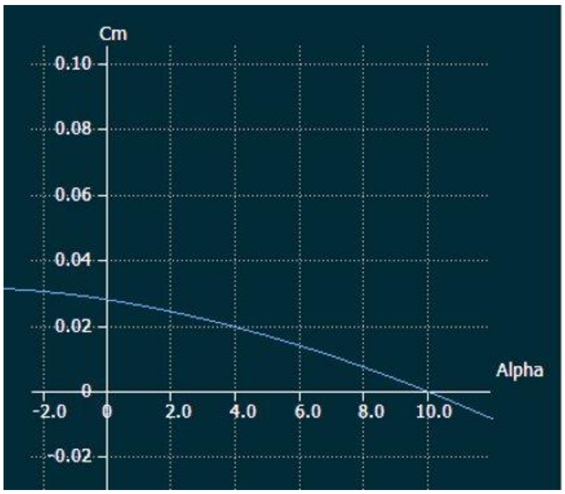


Figure 13: Stability plot according to XFLR5

As XFLR5 uses a more general method to calculate stability, we concluded that the program is not accurate for canard planes, as this AoA is after the stalling (flow separation) has begun for our plane and just 2 degrees below the max stall AoA.

CFD

CFD were performed for the following 3 AoA values. Zero degree, which would be the starting AoA, 5-*degree* AoA, which will be the takeoff AoA, and 12-*degree* AoA, where the plane is expected to stall. In the plots, red values mean higher turbulence/vorticity values and blue values mean lower turbulence/vorticity values. The canard is the left-most wing, and the tail wing is the right-most wing. The other wing is the main wing.

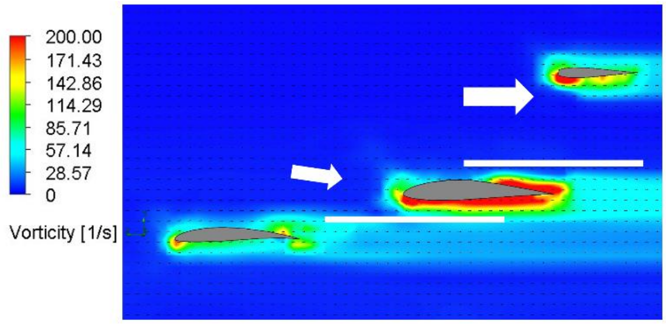


Figure 14: CFD for the zero-degree AoA

The white lines show the boundary layers for the turbulence produced by each wing. The dark blue regions show the free-stream air flow speed. Notice that around airfoils, the airflow speed increases. As shown by boundary layers, the airflow from the canard does not affect the main wing, and airflow from the main wing does not affect the tail wing, as no flow from the canard goes over the main wing and no flow the main wing goes over the tail wing. Hence, at zero-degree angle of attack, the plane is stable and does not stall. Then the same simulation was done for the takeoff AoA, 5 *degrees.*

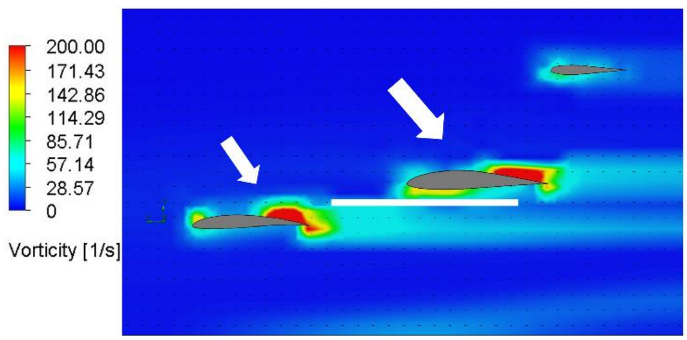


Figure 15: CFD for 5-degree AoA

While there is more turbulence compared to the zero-*degree* AoA, there is no affect from the canard flow on the main wing or the main wing floe on the tail wing as shown by the boundary layer. Therefore, the plane does not stall at the takeoff angle of attack, 5-*degree.* The same CFD simulation was performed for the 12-*degree* AoA, where the plane is expected to stall.

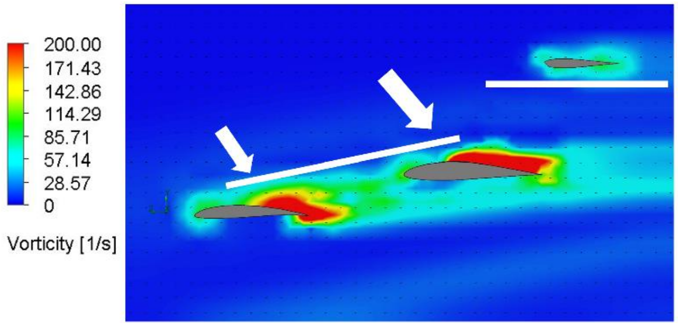


Figure 16: CFD for 12-degree AoA

The plane is expected to stall at 12-*degree* AoA. According to the CFD image above, the boundary layer from the canard flow extends over the main wing. Medium speed (green) flow is going over the main wing. This turbulence suggests the plane is stalling at this angle. Hence this validates that the plane is not stable at this angle of attack.

Wind Tunnel

Similar to CFD, wind tunnel tests were performed for zero *degree*, 5-*degree* and 12-*degree* AoA values. Smoke images taken for those AoA values. They show streamlines (airflow lines) around the wing. With the equipment available to us at the FCAAP sub-sonic wind tunnel, we had to select a small region for the smoke flow study as the laser beams had to be focused to a certain region. As the stall occurs from the main wing and the tail is further up from the other wings (as shown by the CFD, tail wing is not affected by the main wing or the canard flow), the region around the canard and the main wing was considered.

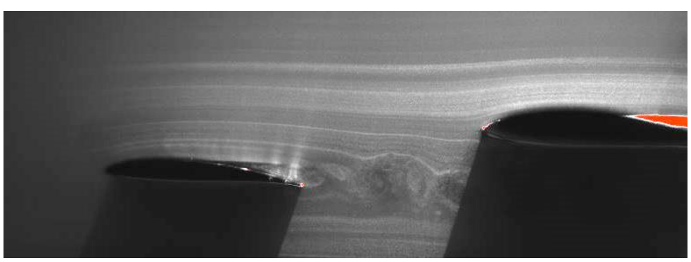


Figure 17: Streamlines for zero-degree AoA.

The flow follows the airfoil shape except at the tail for the canard. However, the disturbance caused there does not affect the main wing. The airflow at the front (LE) of the main wing is not affected by the main wing. Hence, there is no effect on the lift produced by the main wing. Therefore, this matches with the CFD and proves the stability plot conclusion that the plane is stable at zero-*degree* AoA.

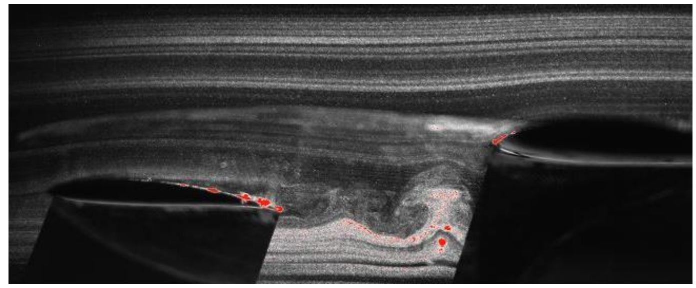


Figure 18:Streamlines for 5-degree AoA.

For the 5-degree AoA, there is more turbulence at the TE of the canard, but it still does not affect the main wing. The airflow is darker here, which means that the intensity is higher, which is expected as higher AoA accelerated the velocity of the flow around the main wing. Like the precious case, this does not show stalling for our plane as the flow disturbances do not interact with each other. this matches with the CFD and proves the stability plot conclusion that the plane is stable during take-off AoA.

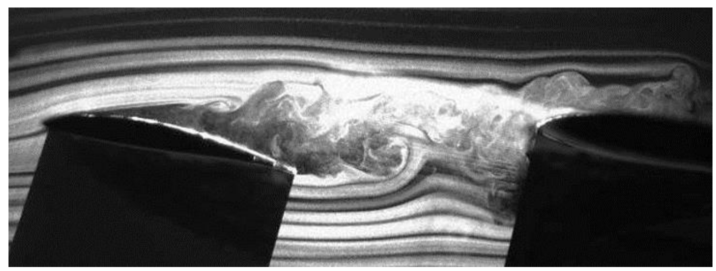


Figure 19:Streamlines for 12-degree AoA.

Based on stability calculations/simulations and CFD, the plane is expected to stall at 12-*degree* AoA. The smoke image does confirm this. There is a much larger flow separation, starting from the middle of the canard, and it affects the LE of the main wing and flows over the main wing. Hence, as the flow is not attached to the main wing, the main wing will not produce the amount of lift expected at this AoA. Therefore, the plane is stalling. This validates the stability calculations and CFD done for this AoA.

Conclusion

The theoretical stability calculations showed that when the plane has a 2-wing layout with the canard and the main wing, it does not achieve a stable flight. However, with the addition of a tail wing, it does. The XFLR5 simulations validated this. Furthermore, it showed that the plane stalls at a 12-*degree* AoA. Both the CFD and the wind tunnel tests performed on the plane at zero-*degree*, *5-degree* and 12-*degree* AoA values are very similar. Furthermore, they prove that the plane is stable at zero and 5-degree angles and is not stable, and stalling, at the 12-degree AoA value. Therefore, we can conclude that a canard wing cargo plane can be stabilized with the addition of a third wing, a tail stabilizer. Furthermore, the theoretical calculations and equations discussed in this paper provide values that are valid for the design. CFD method used in this paper is accurate as they show similar results to the wind tunnel test data.

References

[1] J. D. Anderson, "Fundamentals of Aerodynamics," 5th Edition, McGraw Hill Publications., 2011.

Acknowledgements

The wind tunnel data was collected and processed by Devon Foster, a master's student at Florida State University, according to the team's requests. Thank you Dr. Rajan Kumar and Dr. Chiang Shih for their contributions.

Thank you to the geometric team members, Jacob Pifer, Lauren Chin and Joseph Figari, in helping us with test prints and data collection.

Definitions/Abbreviations

SAE	Society of Automotive Engineers
AoA/α	Angle of Attack
C_m	Coefficient of Moment
C_L	Coefficient of Lift
C_D	Coefficient of Drag
R/C	Remote Control
CG	Center of Gravity
CFD	Computation Fluid Dynamics
CAD	Computer Aided Design
LE	Leading Edge
TE	Trailing Edge

Appendix

Stability Calculations

Contents

- Known Values
- Cm vs AoA plot (Reference - FOA)
- equilibrium values (Reference - FOA)

```
clear all;
clc;
close all;
%Stability Calculations + Equilibrium Values
%Sasindu Pinto
%Values in US Units, (in,lbf) :

%References
%FOA - Fundamentals of Aerodynamics - John D. Anderson
%AD - Aircraft Design, A systems Engineering Approach - Mohhamad H. Sundraey
%AT - airfoiltools.com

%profiles
%canard - E214
%aft (main) - E197
%tail - Epller 168

%Load properties of wing profiles
load("E_214_Properties");
load("E197_Properties");
load("Eppler_168");
load("E_668");
```

Known Values

```
rho=0.0023769/1728;    %slugs/ft3 / 1728 to get value in inches

%Chord lengths
Chord_canard=12;
Chord_aft=14.5;   %Main wing
Chord_tail=8;

%Wing spans
Wingspan_canard=49;
Wingspan_aft=68;    %Main wing
Wingspan_tail=26.5;

%Maximum  thickness of each wing (Reference - AT)
thickness_max_canard=Chord_canard*0.111;
thickness_max_aft=Chord_aft*0.1349;
thickness_max_tail=Chord_tail*0.124;

%Velocity conversion to in/s
V_selected_in=25*17.6;

%Dynamic pressure in inches (Reference - FOA)
q=0.5*rho*V_selected_in^2;
```

```
%Aspect Ratio (Reference - FOA)
AR_canard=Wingspan_canard^2/(Chord_canard*Wingspan_canard);
AR_aft=Wingspan_aft^2/(Chord_aft*Wingspan_aft);
AR_tail=Wingspan_tail^2/(Chord_tail*Wingspan_tail);

%Characteristic Length for Lift (Reference - FOA)
S_canard=Chord_canard*Wingspan_canard;
S_aft=Chord_aft*Wingspan_aft;
S_tail=Chord_tail*Wingspan_tail;

%Characteristic Length for Drag (Reference - FOA)
T_canard=Chord_canard*thickness_max_canard;
T_aft=Chord_aft*thickness_max_aft;
T_tail=Chord_tail*thickness_max_tail;

%AoA = 5 deg, based on aero preformance (Reference - AT)
CL_canard=1.1167;  %at AoA
CL_aft=0.887;    %at AoA
CL_tail=0;

%AoA = 0 deg, (Reference - AT)
CL_canard_0AoA=0.6;
CL_aft_0AoA=0.35;
CL_tail_0=0;

%from Stability_File2 - CG positions
CG_x=21;%21.6;%21.6365;%28.3787%39.7086;
CG_y=1.9;%2.5889;
M_total=14;%13.62; %12.3 rounded up to 13;

%canard position from the CAD file
x_c=CG_x-(2.62+(0.25*Chord_canard));
y_c=5.71-CG_y;

%aft position from the CAD file
x_a=24.63+(0.25*Chord_aft)-CG_x;
y_a=CG_y-(1.43);

%tail position from the CAD file
x_t=35.53+4.1+(0.25*Chord_tail)-CG_x;
y_t=10+CG_y;

%canard L/D (Reference - AT)
L_c=E214_Prop(1:73,2)*q*S_canard;
D_c=E214_Prop(1:73,3)*q*T_canard;

%aft L/D (Reference - AT)
%L_a2=E197_Prop(1:73,2)*q*S_aft;
%D_a2=E197_Prop(1:73,3)*q*T_aft;
L_a=E197_Prop(1:73,2)*q*S_aft;
D_a=E197_Prop(1:73,3)*q*T_aft;
%tail L/D (Reference - AT)
L_t=Eppler_168(1:73,2)*q*S_tail;
D_t=Eppler_168(1:73,3)*q*T_tail;
```

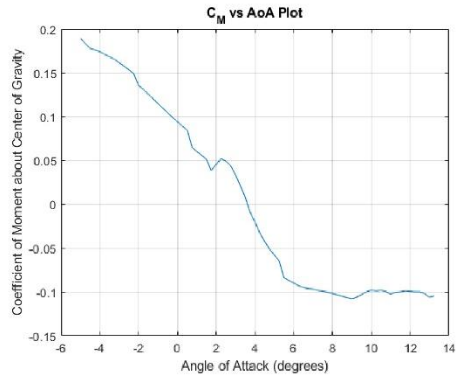
```
%moments (Reference - AT)
M_AC_C=E214_Prop(1:73,5)*q*S_canard*Chord_canard;  %canard
M_AC_M=E197_Prop(1:73,5)*q*S_aft*Chord_aft;  %main
%M_AC_M=E_668(1:73,5)*q*S_aft*Chord_aft;  %main
M_AC_T=Eppler_168(1:73,5)*q*S_tail;  %tail
```

Cm vs AoA plot (Reference - FOA)

```
alphaA=E214_Prop(1:73,1);   %AoA in deg
alphaR=E214_Prop(1:73,1)*pi/180;    %AoA in rad
%alphat=transpose(alpha);   %Tranpose of AoA (used for density plot)

%Moment about CG
M_CG=L_c*x_c + L_c.*(alphaR).*y_c - D_c*y_c + D_c.*(alphaR).*x_c - L_a*x_a - L_a.*alphaR.*
y_a...
    + D_a*y_a - D_a.*alphaR.*x_a - L_t*x_t - L_t.*alphaR.*y_t + D_t*y_t-D_t.*alphaR.*x_t..
.
    + M_AC_C + M_AC_M + M_AC_T;

%Coefficient of Moment about CG
C_M_CG = M_CG./(q*S_aft*Chord_aft);
figure(1)
plot(alphaA,C_M_CG)
title("C_M vs AoA Plot")
xlabel("Angle of Attack (degrees)")
ylabel("Coefficient of Moment about Center of Gravity")
grid on
```



equilibrium values (Reference - FOA)

```
CM_Eq=find(round(C_M_CG,1)==0)  %Equilibrium CM
AoA_Eq=alphaA(32,1) %Equilibrium AoA
CM_at_0=C_M_CG(21,1)    %CM at AoA = 0
C_L_trim=E197_Prop(32,2);   % CL for the main wing at equilibrium

% minimum speed required at equilibrium
V_trim=sqrt(2*M_total/(rho*S_aft*C_L_trim));    %Speed in in/s
V_trim_mph=V_trim/17.6  %Speed in mph
```

```
CM_Eq =

    28
    30
    31
    32
    33
    34
    35
    36
    37
    38


AoA_Eq =

     3


CM_at_0 =

    0.0939


V_trim_mph =

   10.2904
```

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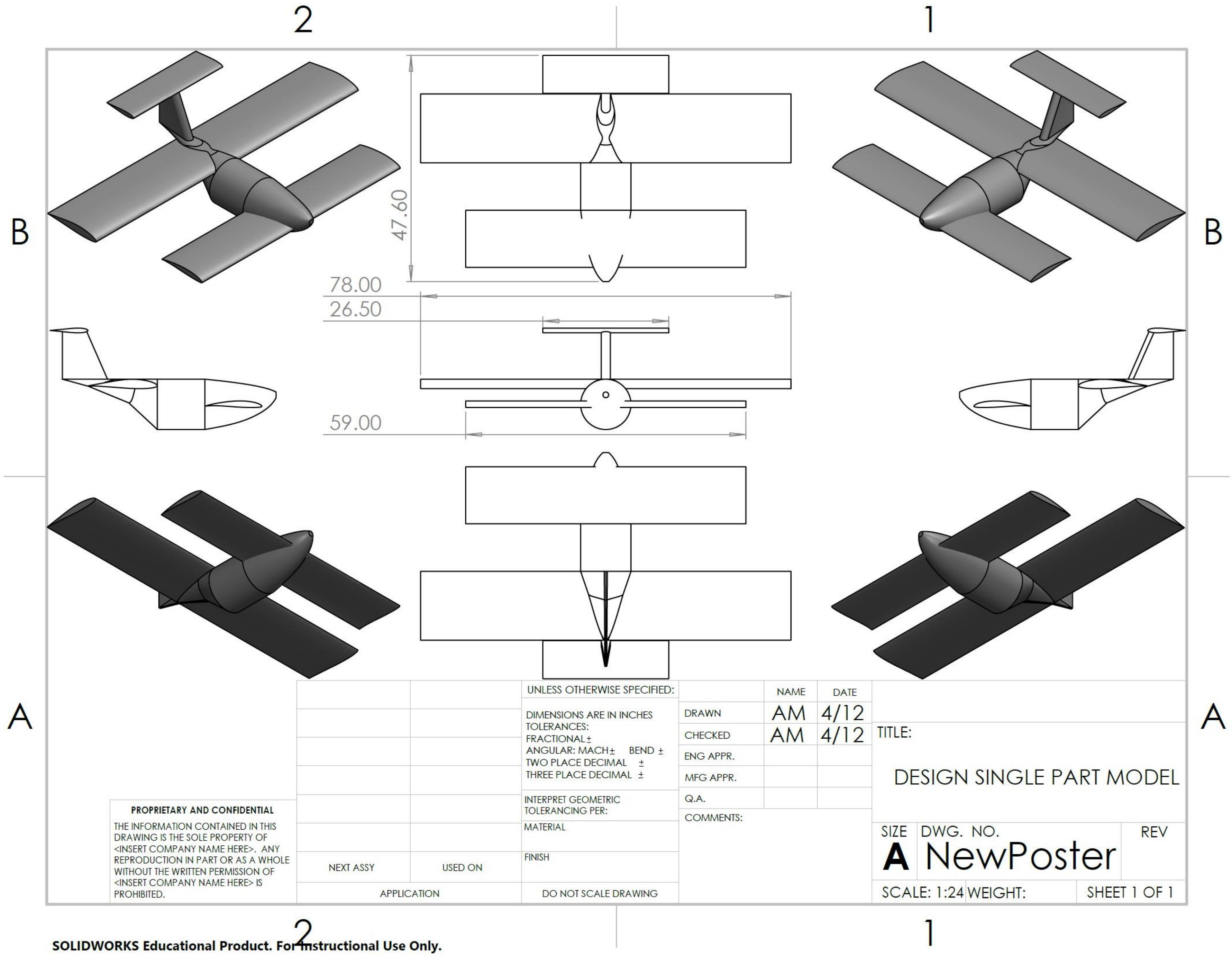
CAD Drawings

(On the next page)


47.60
78.00
26.50
59.00
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN AM 4/12
CHECKED AM 4/12
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
DESIGN SINGLE PART MODEL
SIZE
A
DWG. NO.
NewPoster
REV
SCALE: 1:24
WEIGHT:
SHEET 1 OF 1
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