Department of Mechanical Engineering

Structure design and analysis for a small-scale wing in ground (WIG) vehicle

In partial fulfillment of the requirements for the

Degree of Bachelor of Engineering

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Submitted by

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Abstract

This project is an industrial collaboration with Wigetworks Pte Ltd, a company specializing in the commercialization, research and design of WIG crafts. The project serves to design, analyze, experiment, test and build a small scale Wing in Ground (WIG) vehicle in order to investigate ground effects. It covers a wide range of engineering work processes and due to the realistic nature and wide scope of the project, it can be made comparable to real life engineering projects, which engineers deal with in their course of work. This project was presented in the recent RSAF Aerospace Technology Seminar 2005.

The project starts with the conceptual design phase whereby the general shape, design and layouts of the WIG craft are determined. This is then followed by the structural design of the WIG craft. Analyses were carried during the design phase with the aid of computer-aided engineering. Packages like Fluent and SolidWorks - COSMOWorks were used to carry out the analysis. Fabrication is then followed to obtain a prototype that is able to demonstrate the effects of ground effect.

In the short 9 months of the project, the project team has successfully managed to design, analyze, fabricate and achieve a working WIG craft. Field trials have shown that the fabricated WIG craft is able to demonstrate the concept of ground effect on small-scale vehicles. The fabricated WIG craft has also achieved versatility by being amphibious, working on both land and water.
Acknowledgements

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Wigetworks Pte Ltd for supporting this project.

Last but not least, to all of the author’s friends who have helped and encouraged the author in one way or another during the project.
WIG is an abbreviation of Wing In Ground-effect. A WIG craft sits on a layer of air cushion created by aerodynamics rather than by an engine in the case of a hovercraft. This means that it only exists when the WIG craft has sufficient forward speed. This is called a dynamic air cushion as opposed to the hovercraft’s static air cushion. This air cushion reduces the friction drag of the WIG craft with water, which makes it a more efficient vehicle compared to convention marine craft.

WIG craft have been around for decades. In the past 40 years a large number of different WIG craft have been designed and built. However there are still a very limited number of literatures written on it. The effects of ground effect on small-scale vehicles are virtually unexplored. Therefore this project, aims to design, analyze, fabricate and experiment a small scale wing in ground craft to demonstrate the effects of ground effect.

This is a joint effort of 4 final year project students covering 4 different areas of interest; aerodynamics, structures, propulsion and stability and control. In this thesis, the structural aspects of the WIG craft will be covered. Including the structural design, analysis and experiments carried out.
1.1 Objective

Although WIG crafts is in existence and many WIG crafts were design in the past 40 years by various countries, there is however only a limited amount of published literature and data on the design of WIG crafts. The objective of this project is to design and build a small-scale WIG craft in order to investigate ground effect.

1.2 Project Scope

The small-scale WIG craft structures will be

1) Designed
2) Analyzed to ensure that it can withstand forces and loads during flight,
3) Designed modularly so as to allow for easy transportation, maintenance and testing.
4) Fabricated
1.3 Structure of Dissertation

This thesis is divided into 8 chapters and the chapters are as organized as follows:

Chapter 1- contains the introduction of Wing in Ground craft, overview, objective and scope of the project.

Chapter 2- contains the literature review of airframe design and structures, as well as the range of loads that can be generated on an airframe.

Chapter 3- describes the conceptual design of the WIG craft. Followed by the structural design and the modular design. It also describes the methods of fastening the modular units temporarily.

Chapter 4- discusses on the material selection process for the construction of the small-scale WIG craft, the glue to be used for bonding parts together. It also discusses results from both computer aided engineering and theoretical calculations.

Chapter 5- discusses the experimental stress analysis performed on the individual modular units of the WIG craft, shows the breakdown of final weight of the craft and describes the experiment carried out to determine the C.G. of the WIG craft.

Chapter 6: describes the sea trials / flight tests of the different prototypes and resultant findings. Videos are available in the included CD-R for further observation.

Chapter 7: Projection conclusion

Chapter 8: Recommendations
Chapter 2: Literature review

2.1 WIG craft design features

A WIG craft usually operates on water and flies close to the water surface whenever it is in ground effect. This makes it partially an air vehicle, which can be made comparable in terms of structures to aircrafts and seaplanes. For a WIG craft, airframe components are used to form part of the overall structure of the vehicle. Basically, any WIG craft design can be simplified into four major components.

1) The wing 2) fuselage 3) tail unit 4) Mountings for all other systems

Each component is designed to perform a specific task during operation so that the vehicle can travel smoothly and safely.

The wing - The wing must generate enough lift from the airflow over it so as to support the air vehicle in flight. The total lift produced must be equal to the weight of the aircraft. To take off, the required lift must be developed at a low speed. This can be achieved by the aid of lift augmenting devices, such as the power augmentation ram (PAR) in WIG vehicles, to make it possible. A wing produces lift by creating unequal pressures on its top and bottom surfaces caused by incidence, camber or a combination of both. An example of a chord wise pressure distribution is as shown in fig 1\(^3\) whereby vertical lift and horizontal drag resultants act at the center of pressure.

![Fig 1 Cord wise pressure distribution](image1)

![Fig 2 Typical span wise lift distribution](image2)

For span wise distribution, the typical pressure distribution is as shown in fig 2\(^4\), whereby the maximum loading for a wing alone design is in the middle where both left
and right wings meet. The presence of the fuselage reduces the lift of the wing in the area adjacent to it, resulting in a reduction in effectiveness of the wing very close to the root, producing the dip at the center. (Figure 2) The distributed lift load creates a shear force and bending moment, both of which are at their highest values at the point where the wing meets the fuselage. The structure at this point needs to be strong to resist the loads and moments and at the same time stiff to reduce wing bending.

**The fuselage** - Basically, the fuselage forms the body of a WIG craft, serving the purpose of carrying the payload. It also function as the main structural link between the wing and tail, holding them at correct positions and angle of attack to the air flow, so as to allow the air vehicle to fly as designed to do so. Unlike the wing, which is subjected to large distributed air loads, the fuselage is subjected to relatively small air loads. The main and primary loads on the fuselage would instead be the forces transmitted from other airframe components attached to it, particularly the wing and tail.

During flight, the wings support the fuselage, with another force from the tail that may act upwards or downwards depending on the design of the craft. The weight of the fuselage structure and payload will cause the fuselage to bend downwards from its support at the wing. Together with other loads from the tail and other components that may be present, this results in bending loads to act on the fuselage.

**The tail** - The tail unit usually consists of a vertical fin with a movable rudder and a horizontal tail plane with movable elevators. These surfaces provide stability and control in pitch and yaw. The tail is usually far from the center of gravity, to provide a large lever and moment. For this reason, it is placed at the rear of the fuselage. Like the wing, the tail plane produce lift forces. Depending on the size, incidence and design of the tail, for
lifting tail design, the span wise and cord wise load distribution can be said to be similar to the wing. Therefore like the wing the distributed lift load creates a shear force and bending moment, both of which are at their highest values at the point where the tail meets the fuselage.

2.2 Characteristic of airframe structures

The wing and tail unit forms the major airframe component of a WIG craft. Most of the airframes are made up of 4 main types of structural member, namely spars, stringers, ribs and skin. The spar is a heavy beam running span wise to take transverse shear loads and span wise bending. Wing ribs are planar structures capable of carrying in planeloads and are placed chord wise along the wingspan, supported by the span wise spars. Besides serving as load re-distributors, ribs also hold the skin stringer to the designed contour shape. Ribs reduce the effective buckling length of the stringers and thus increase their compressive load capability. The cover skin of the wing forms an efficient torsion member. For some air vehicles traveling at subsonic speeds, the skin is relatively thin and may be designed to undergo post buckling. Thus the thin skin can be assumed to make no contribution to bending of the wing and the bending moment is taken by spars and stringers. Figure 3 shows a typical wing cross section for a subsonic wing.

Figure 3 typical cross section of wing
Chapter 3: Design of WIG

3.1 Conceptual Design

In this design phase, the overall shape, dimensions and weight of the WIG craft is determined. Factors like dimensions and size are determined considering structural constrains. However factors like the shape of the WIG craft are determined based on non-structural considerations. For instance, the airfoil of the wing and tail is chosen according to the aerodynamic lift characteristics and it is sized to give the required lift. This is done by Mr Ng Geok Hean (AM 90 Aerodynamics) to give the required lift of 2kg based on the estimated weight. The hull form was chosen and designed for the fuselage is based on hydrodynamic considerations. The exact shape and contours of this hull form was by colleague Mr. Toh Boon Whye (AM92 Hydrodynamics and propulsion). The layouts of the wing, tail and propulsion components are decided by Mr. Jonathon Quah Yong Seng. (AM93 control and stability)

3.2 Weight Estimation

The breakdown of the weight for the WIG craft is estimated and shown in Appendix I (page i). The total weight of the craft is estimated by adding up the total weight of all the components that would be used.

To account for changes or improvements or additions to the WIG craft, an additional 25% of the weight is added.

Therefore total estimated weight = 1.6 x 1.25

\[ \approx 2\text{kg} \]
3.3 Conceptual design drawing

Finalized Conceptual Design

WIG Craft

Fig 4a: Isometric View
WIG Craft

Fig 4b: Conceptual design - Top View

* All dimensions in mm
WIG Craft

Fig 4C: Conceptual design - Front View

* All dimensions in mm
WIG Craft

Fig 4D: Conceptual design - Side View

* All dimensions in mm
3.4 Modular Design

A modular designed WIG craft is also intended for to allow for the disassembly and interchangeability of parts. This accommodates for the changing of parts as well as easy maintenance, transportation and testing. This ability for the disintegration of the WIG craft gives rise to smaller components known as modular units.

The WIG craft is designed to be able to be separated into modular units.

They are:

1) 1x Fuselage
2) 1x Engine Mount
3) 1x Power Augmentation Ram arm
4) 1x Vertical Fin
5) 1x Tail
6) 2x Wing
7) 3x Electrical motors with propellers

Total number of parts: 10

3.5 Structural design

As the WIG craft can be considered as an air vehicle. One main difference between the WIG craft structures and materials and other engineering structures and materials lies in the weight. The main influential force in this WIG craft design is to reduce weight and at the same time being strong enough to withstand the forces acting on it during flight. Therefore materials in general for the small scale WIG craft must have a high strength to weight ratio so as to be deemed suitable for the WIG craft application.

The WIG craft structures must be designed to ensure that every part of the material is used to its full capability. This leads to the use of airframe structures, which requires the assembly, and joining of numerous parts together. As stated in section 3.1, most of the
size and shape of the WIG craft structural component are determined based on non-structural considerations, thus the structure must also maintain the shape of the design. Components like servos, electrical engines and propellers are also used. The WIG craft is thus also designed taking into accounts the dimensions of the required components, weight and availability of these various components.

### 3.5.1 Wing

The wing is given an airframe design to drastically reduce the overall weight of the WIG craft. Two spars, one located at quarter chord and the other at half chord to take the transverse shear loads and span wise bending. These two spars also help to support the five wing ribs that are placed chord wise along the wingspan to prevent buckling of the ribs. The wing ribs are placed at increasing intervals, from the end meeting the fuselage, to carry the in planeloads. This is required as the nature of span wise lift force distribution over the wing (shown in figure 2) is such that a higher lift force is experienced closer to the fuselage. Besides serving as load re-distributors, these ribs also hold the skin stringer to the designed contour shape. Skin stringers are used and placed span wise above the ribs. As these stringers are not fixed to the fuselage, they are not designed to support span wise bending. Their function is merely to maintain the overall airfoil shape of the wing. (Figure 5)
### 3.5.2 Horizontal Tail

Similar to the wing, the tail is designed to have an airframe structure. 2 spars, both at quarter chord are used to take the span wise bending and support the ribs. Due to the short span of the horizontal tail, only 3 ribs on each side are placed chord wise along the wingspan to take the in planeloads to reduce the weight of the craft. (Figure 6)

![Fig 6 Structural design of tail](image)

![Fig 6a Top View of tail](image)

### 3.5.3 Engine Mount

The design requirements for the engine mount are such that it must be elevated high enough so as to prevent the 8-inch propeller from touching the fuselage and be attachable to the vertical fin. A horizontal beam like structure with a rectangular hole in the middle serves to carry the motor. This beam is jointed to 2 vertical plates (by the use of finger lock joints), which will be used to clamp onto the vertical fin through the use of bolt and nuts. (Figure 7)

![Fig 7 Structural design of Engine Mount](image)

![Fig 7a Side view of Engine Mount](image)

![Fig 7b Top view of Engine Mount](image)

*All dimensions in mm*
3.5.4 Power Augmentation Ram (PAR)

The PAR requires 2 motors at the bow of the fuselage, one ahead of each wing to assist in take off. A variation of airflow direction from the motors is also required due to the nature of operation of the WIG craft. The PAR Arm is thus designed to have a simple horizontal rectangular beam design fixed in the middle to a hinge and holding a motor on each side of the arm. This horizontal beam design also has an advantage of restricting deformation due to the trust force of the engines, as a beam is very stiff when loaded across its width. A servomotor in the fuselage can then control the angle of tilt of this beam. (Figure 8)

![Fig 8 Structural design of PAR](image1)

![Fig 8a Top view of PAR](image2)

3.5.5 Vertical Fin

The height of the vertical fin takes into account the size of the propellers of the motor that will be fitted onto it, such that there is enough clearance for the propeller to move freely. It is designed with a larger bottom to make it stable. At the top, is a horizontal platform for the horizontal tail to rest upon. The whole structure is supported by a base plate that will further stabilize the design and at the same time it used for fastening the fin to the fuselage. (Figure 9)
3.3.6 Fuselage

It is required for the fuselage to hold the tail unit, wings and the PAR arm together. The front half of the fuselage has a relatively thick wall, so as to withstand the bearing stress transmitted through the spars due to the lift force on the wing. This also provides the stiffness required against bending due to the operation of the PAR. The rear half portion of the fuselage has an internal truss structure due to its triangular geometric shape and at
the same time as the wings are not slotted through this rear section, it allows for a thinner wall which will reduce the weight of the fuselage. (Figure 10)

Fig 10 Structural design of Fuselage

Fig 10a Side View of Fuselage

Fig 10b Top View of Fuselage

Fig 10c Rear View of Fuselage

*All dimensions in mm
3.6 Methods of fastening

3.6.1 Engine Mount

The engine-mount made entirely of Birch Aircraft plywood holds a motor, which is secured by means of four pairs of 3mm stainless steel bolt and nuts to the horizontal beam of the engine mount. The entire mount with the motor is connected to the vertical fin during operation, such that the motor is placed at an elevated height above the fuselage. Three pairs of 3mm stainless steel bolt and nuts are used to fix the engine mount to the vertical fin. (Figure 11)

![Fig 11 Engine Mount - side view](image1)

![Fig 12 Engine mount - top view](image2)

3.6.2 PAR arm

The PAR arm is a single modular unit made of Birch Aircraft plywood, which can fit 1 motor at each end of the arm. The motors can be connected and disconnected easily to the arm by means of two pairs of 3mm stainless steel bolts and nuts through the holder of the motors. The whole PAR arm is connected to a hinge at the bow of the fuselage by means
of another 3 pairs of stainless steel bolt and nuts, allowing the variation of angle of tilt of the PAR when in operation. (Figure 14)

![Fig 13 PAR](image1)
![Fig 14 PAR connected to hinge](image2)

3.6.3 Vertical Fin

The vertical fin with the rudder, made of balsa plywood, serves to hold the horizontal tail and engine mount to the fuselage. The vertical fin is connected by means of six 3mm stainless steel screws to the fuselage and the horizontal top platform serves as a support for the horizontal tail to rest upon. (Figure 15 &16)

![Fig 15 Vertical Fin](image3)
![Fig 16 Vertical Fin - side view](image4)
3.6.4 Wings

The wings consist of two modular sections made of balsa wood; each has two protruding spars (One balsa Spar and one carbon fiber tube) that can be slotted into the fuselage. Four 2.8mm stainless steel bolt and nuts are then slotted through the front spars to lock the wings in position.

![Fig 17 Wings](image1.png)

![Fig 18 Wing mounting](image2.png)

3.6.5 Horizontal Tail

The horizontal tail is made of balsa wood and is a single unit that is bolted onto the top horizontal platform of the vertical fin. This is done by means of two pairs of 25mm long and 3mm diameter stainless steel bolts and nuts.

![Fig 19 Horizontal Tail](image3.png)
Chapter 4 Design analysis

4.1 Material Selection

As mentioned earlier, being an air vehicle, the weight of the WIG craft is an important factor in the design. Other than being light, the craft must be able to float on water as well; making density of the materials used for construction a considered factor. To allow for a light craft to be able to withstand all the forces experienced, a material that has a high strength to weight ratio must also be selected. Stiffness of the material is also important, as it is unwise for the WIG to deform tremendously during operation. Another factor that need to be considered include corrosion caused by exposure to weather and water that the WIG craft would come into contact with. The effect of corrosion is serious as it is likely to degrade the material strength and this may cause failure. Other factors would include availability and cost.

4.1.1 Material Selection for materials used for construction of WIG craft

Several different types of materials are possible to be used as the main material for the fabrication of the WIG craft. Besides having a good strength to weight ratio and stiffness, the main materials considered to be suitable in the construction of the WIG craft in this project would however still largely lie on the availability, cost and ease of fabrication due to time constrain. The materials considered during the design phase include balsa wood, birch aircraft plywood, polystyrene and fiberglass. Appendix II (page ii) summarizes the ranking of the materials based on the different factors.

The balsa wood was selected due to the high strength to weight ratio and the fact that it is easy to fabricate and it is easily obtainable in the market with low cost. The low density
of balsa wood of around 140kg/m$^3$ also gives it an advantage, as it allows it to float by itself on water. However balsa wood has got a relatively low stiffness compared to other materials and it also undergoes plastic deformation easily when subjected to high concentrated load. Therefore Birch Aircraft plywood is used to reinforce the main balsa structure wherever high loading is experienced.

### 4.1.2 Material Properties

Tensile tests are performed on the samples of the balsa wood and plywood using the Instron machine found at the strength of materials lab to determine the material properties of the materials used for construction of the WIG craft. The balsa wood is tested in the longitudinal direction (along the grains) and in the tangential direction (against the grains). The following graphs show the force vs. extension curves of the balsa wood and Birch Aircraft plywood. (Refer to Appendix IV for detailed calculations) (page iv)

**Fig 20** Graph of force (N) vs extension (mm) for balsa wood (longitudinal direction)

**Fig 21** Graph of force (N) vs extension (mm) for balsa wood (tangential direction)

<table>
<thead>
<tr>
<th>Elastic Modulus, $E_{\text{balsa}} = \frac{\sigma}{\epsilon}$</th>
<th>216MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield strength</td>
<td>5.68MPa</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Elastic Modulus, $E_{\text{balsa}} = \frac{\sigma}{\epsilon}$</th>
<th>23.1MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield strength</td>
<td>0.533MPa</td>
</tr>
</tbody>
</table>

Table 1: Balsa wood – against the grain

Table 2: Balsa wood – against the grain
4.1.3 Glue

The final structure will mainly consist of only balsa wood and glue, thus the choice of glue is a crucial decision. Sample specimens were broken in two, and then glued back together. Next, the specimens were tested under tension using the Instron machine at the strength of materials lab to determine which glue was the strongest. The three glues that were tested are epoxy, carpenter's wood glue, and cyanoacrylate glue (Appendix III).

Both the wood glue and the cyanoacrylate glue were stronger than the actual wood itself as the wood broke before the glued joint did. The epoxy proved to give the worst results breaking before the wood reaches its fracture point. (Figure 23- glue test results)
Based on the results, the wood glue that was used in testing will be used in the final design with large surface areas whereby clamping of the bonded surface is possible. At parts whereby clamping is impossible and short drying time is required, the dyanoacrylate glue is used.

4.2 Structural Analysis

Structural analysis is done mainly using theoretical calculations and with the aid of computer aided engineering (CAE). It was done to ensure that the craft would not fail structurally under the loads experienced during flight. The designed WIG craft can be separately considered into 6 sections: 1) Fuselage 2) Engine Mount 3) Power Augmentation Ram arm 4) Vertical Fin 5) Wing 6) Tail

4.2.1 Theoretical calculations

4.2.1.1 Fuselage
The fuselage is subjected to bearing stress of 0.115 MPa due to the force by the PAR motors when tilted down with \( F_t = 2.6 \text{N} \) each. It also undergoes a maximum bearing stress of 0.121 MPa due to lift force generated by the wing through the two spars slotted into the fuselage, giving a safety factor of more than 2. When the rear motor is in operation, the fuselage is also subjected to bearing stresses of 0.0205MPa due to rear motor trust force. (Detailed calculations are attached in Appendix V, page viii) Other calculations attached would include the bearing and shear stresses on the screws used and the hinge.

4.2.1.2 Engine Mount
The engine mount is subjected to a downward force \( (F_{mw}) = 0.8 \text{ N} \) and a force due to the trust exerted by the motor \( (F_t) = 2.6 \text{ N} \). The engine mount is subjected to a bearing stress
of 72.3Kpa due to the trust force on the connection between the engine mount and the vertical fin and a bearing stress of 54Kpa due to the on the connection between the engine mount and the motor. Giving a safety factor of more than 2 in both cases. (Detailed calculations are attached in Appendix V, page x) Other calculations included in the appendix include bearing stresses on the stainless steel engine holder and bearing and shear forces on the bolts connecting the engine mount to vertical fin and bolts connecting stainless steel engine holder to engine mount.

4.2.1.3 Power Augmentation Ram (PAR)

The PAR arm is subjected to a downward weight force \( F_{mw} = 0.8 \) N at each end and a force due to the trust exerted by each motor \( F_t = 2.6 \) N. Maximum bearing stresses on the plywood PAR were calculated to be 0.144 Mpa, above the designed safety requirement of 2. (Detailed calculations are attached in Appendix V, page xiii) Bearing stresses on the hinge and the stainless steel engine holder together with the bearing and shear forces acting on the bolts connecting the stainless steel engine holder to the PAR and bolts connecting the PAR to the hinge were also attached in appendix V page xiii.

4.2.1.4 Vertical Fin

The vertical fin is subjected to bearing stress of 28.9Kpa at its base plate and 57.8Kpa at the section where the engine mount is fixed due to the horizontal trust force of the rear motor. (Detailed calculations are attached in Appendix V, page xv) Together with the bearing and shear stresses on the screws connecting the vertical fin to the fuselage, the safety factor of the vertical fin is determined to be above the required value of 2.

4.2.1.5 Wing

When in operation, the upward lift forces on the wing supporting the weight of the WIG craft would result in a bending moment on both spars of the wing to be experienced. As
only both spars are design to pass through the fuselage and the stringers of the wing are not fixed to the body of the WIG craft, it is assumed that the entire bending load is shared and experienced by the spars. A shear force would also be experienced on both spars at the portion nearest to the fuselage. The maximum bending stresses of the spars were calculated and found to be 37Mpa giving the safety factor of 2. While the shear stress on the rectangular spar is found to be 0.078Mpa and 0.146Mpa for the round spar. (Detailed calculations are attached in Appendix V, page xvii)

4.2.1.6 Horizontal Tail

Like the wing, the upward lift forces on the tail would result in a bending moment on both spars of the horizontal tail unit to be experienced. The horizontal tail unit is designed to give a lift force of 400g and the maximum bending stresses on the spars were calculated to be 4.71Mpa giving a safety factor of 3. (Detailed calculations are attached in Appendix V, page xvii)

4.2.2 Stress analysis using CAE

Computer aided engineering (CAE) was used to aid in the stress analysis during the initial phase of the WIG craft. The Finite Element Analysis (FEA), which provides a reliable numerical technique for analyzing engineering designs is used. The process starts with the creation of a geometric model. Then, the program subdivides the model into small pieces of simple shapes (elements) connected at common points (nodes). Finite element analysis programs look at the model as a network of discrete interconnected elements. The Finite Element Method (FEM) predicts the behavior of the model by manipulating the information obtained from all the elements making up the model.
The FEM is a powerful and very versatile numerical method for solving differential equations governing engineering problems. It is a numerical tool used to transform the differential equations into a set of algebraic equations. These algebraic equations can then be solved efficiently by computers. In the finite element method, the problem can be discretized into a finite number of elements and certain methods (e.g. virtual work method, weighted residual method) are employed to transform the governing differential equations into a set of algebraic equations for each element. Then the contribution from each element is assembled to form the overall governing equations of the whole problem including the imposition of the boundary conditions. The governing algebraic equations are solved and the stresses, strains, deformation and other results can be obtained.

The reasons for FEM’s popularity are its versatility and power. Due to its discretization techniques, the FEM can be used to solve problems with very complicated geometry and the quick development of high performance computers has been acting as the driving force for FEM’s quick growth. Another important feature of FEM is that it can be easily adapted to accommodate changes in design. This makes initial studies very easy in finite element analysis.

4.2.2.1 COSMOWorks

In the structural analysis for the WIG craft, the FEM software, COSMOWorks, is used. COSMOWorks is chosen primarily because of its capability to couple with COSMOFlow, computation fluid dynamics (CFD) software, to provide solutions for modeling problems involving fluid structure interaction (FSI). FSI problems exist in the case of the WIG craft, as the airflow across the lifting surfaces causes a resultant force over the structures. This is particularly so in the case of the wing and the horizontal tail.
4.2.2.2 Meshing / Element

Solid meshing is used during the analysis of the fuselage, vertical fin, PAR arm, engine mount and the internal structural elements of the horizontal tail and wings. In meshing the geometric models of the designed WIG with solid elements, a high quality mesh comprising of parabolic tetrahedral elements, is generated. The parabolic tetrahedral element, also know as second order elements, is defined by four corner nodes, six mid-side nodes, and six edges. The following figure shows the schematic drawing of parabolic tetrahedral solid element.

The parabolic tetrahedral element is chosen because it yields better results than linear elements as they represent curved boundaries more accurately and they produce better mathematical approximations.

**Fig 24 Parabolic tetrahedral element**

**Fig 25 Meshes**
4.2.2.3 Material Properties

The main raw materials used for the WIG craft would include balsa wood and birch aircraft plywood. In general materials can be grouped as isotropic materials and orthotropic materials. Balsa wood is an orthotropic material as its mechanical properties are unique and independent in three mutually perpendicular directions, i.e. longitudinal, radial, and tangential directions. The longitudinal axis is parallel to the grain fiber direction; the radial axis is normal to the growth rings; and the tangential axis is tangent to the growth rings. The birch aircraft plywood in this case is assumed to be an isotropic material as its mechanical properties can be said to be the same in all directions. For areas of the WIG craft made by balsa plywood, it is assumed to be an isotropic material with material properties that of balsa wood in the longitudinal direction. These material properties are determined using the Instron machine found at the strength of materials lab. (Detailed results are attached in Appendix IV)

4.2.2.4 FEA results

Figure 26 shows the stress plots of the various units of the WIG craft when traveling at maximum speed of 10m/s, putting the WIG craft at maximum loading. Results of the displacement plots of the WIG craft are attached in appendix (VI).

4.2.2.4.1 Fuselage

Shown in figure 26a, the fuselage is subjected to a maximum stress due to stresses caused by the lift force generated by the wing mounted onto the fuselage. The entire fuselage is subjected to an upward bending force caused by the lift force from the wing, tail and trust force of the PAR. It also experiences a torsional load when the rudder is deflected, resulting in a slight twist. (Refer to displacement plot of fuselage in Appendix VI)
4.2.2.4.2 Wing

Figure 26b shows the stress plot of the wing when subjected to a lift force of 1kg, the maximum lift force generated on the wing at the maximum speed of 10 m/s of the craft. The stress plot of the wing shows the spars subjected to a bending load and the maximum stress of the wing is found to be at the roots of the two spars due to the high lift force generated by the wing closer to the fuselage, giving a value of 10 Mpa.

4.2.2.4.2 Engine Mount

Figure 26c shows that the stress plot of the engine mount when subjected to a maximum trust force by the engine and the weight of the motor. The maximum stresses are experienced on the beam like horizontal structure of the engine mount. Like normal cantilever beams, the maximum displacement is found to be at the tip of the horizontal beam like structure.

4.2.2.4.2 PAR

The PAR experiences maximum stress caused by the trust of the motors. As shown in figure 26d, forces acting on the PAR cause maximum stress to be experienced due to the bearing forces acted upon between the bolts and the PAR.
4.2.2.4.2 Vertical Fin

Figure 26e shows the stress plot of the vertical fin. The vertical fin experiences the highest stresses of 0.6Mpa on its base plate due to the lift force generated by the tail resulting in bending force acting on each side of the plate. Putting the base plate in compression.

4.2.2.4.2 Horizontal Tail

Similar to the wing, the horizontal tail experiences maximum stresses on the spars due to the lift force of 400g generated, resulting in a bending load, as shown in figure 26f.
From the results of the stress plots shown for the WIG craft traveling at the maximum allowable velocity of 10m/s, the maximum stress of 10MPa was found to be at the wing root, at the section of the round spar, closest to the fuselage. Analysis was done on the craft for different speeds and it was found that the wing root is the most critical area in the designed WIG craft that is subjected to the highest stress when the craft travels at above 2m/s. The graph below (Figure 27) shows the variation of stress at the wing root against velocity based on the results obtained from COSMOWorks.

From the above result, it can be approximated that the maximum stress for the WIG craft is related to its velocity by the equation

\[ \sigma_{\text{max}} = 0.1 \times V^2 \text{ MPa} \quad \text{for } 2\text{m/s} < V < 10\text{m/s} \]

At velocity of lower than 2m/s, the maximum stress is equivalent to the maximum stress on the engine mount

Implying that \[ \sigma_{\text{max}} = 9.05 \text{ MPa} \quad \text{for } V \leq 2\text{m/s} \]
Chapter 5 Experimental Analysis

5.1 Experimental stress analysis

Structural testing is done on the fabricated craft to verify the calculations and values obtained in FEA, done during the analysis phase. Due to the small size of the WIG craft and limitations in equipment, stress values cannot be obtained while the craft is in operation. Static loading is done instead on the craft to simulate the operating conditions, so as to obtain the stress values on the craft during flight. Experimental stress analysis is the strictly practical branch of stress analysis and for most problems it relies heavily on strain measurement techniques. These measurements can be obtained in general by involving the use of strain gauges, particularly electrical resistance strain gauges. These small and simple devices are used primarily in the experimental stress analysis of the WIG craft. The quarter bridge circuit configuration is used in the experiment, as it can be assumed that there is no temperature variation during the experiment. (Refer to appendix VIII for experiment details)

5.1.1 Fuselage

The largest force that the fuselage would encounter would be at the section whereby the wings meet the fuselage. The fuselage is tested with a 1kg load placed on each wing to simulate the 2kg lift force generated to lift the WIG craft. A linear foil strain gauge is placed adjacent to the hole for slotting the wings to determine the stress value on the fuselage due to the lift generated by the wing.
The stress value of $2.78 \times 10^5$ Pa obtained in the experiment is about the same as the value calculated in FEA. Verifying the stresses calculated.

### 5.1.2 Engine Mount

The engine mount is tested by fixing it into position and running the motors at full throttle while the craft is clamped down with the use of clamps. The horizontal beam of the engine mount can be seen as a cantilever beam subjected to a bending load due to the weight of the motor and an axial load due to the thrust force. A linear strain gauge is placed on the beam so as to obtain the stress values it is subjected to.

#### Table 4: Experiment results for fuselage;

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>$E_{\text{balsa wood (longitudinal)}}$</td>
<td>$216 \times 10^6$ Pa</td>
</tr>
<tr>
<td>$\varepsilon$ (µ)</td>
<td>1287</td>
</tr>
<tr>
<td>$\sigma$ (Pa)</td>
<td>$2.78 \times 10^5$</td>
</tr>
</tbody>
</table>

#### Table 5: Experiment results for engine mount;

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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{plywood}}$</td>
<td>$1.46 \times 10^9$ Pa</td>
</tr>
<tr>
<td>$\varepsilon_{\text{max}}$ (µ)</td>
<td>$295 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\sigma_{\text{max}}$ (Pa)</td>
<td>$4.31 \times 10^5$</td>
</tr>
</tbody>
</table>
The strain values indicated on the strain indicator shows a maximum value only at the initial stages of the test. This is due to the depletion of the power supplied to the motors over time. The value of $\sigma_{\text{max}}$ obtained is lower than that obtained in FEA (Appendix VI). This could be due to the engine trust force being lower than the value defined in FEA, as a result of losses due to wiring and a drop in efficiency in the motor.

5.1.3 PAR

The PAR arm, similar to the engine mount is tested with the craft fixed and the motors running at full throttle. The PAR arm structure is subjected to bending load due to the weight of the motors it is carrying and another bending load due to the trust force supplied by the motors. A linear strain gauge placed on the beam of the structure to measure the strain due to the weight of the motors and another placed on the plane into the paper to measure strain due to the bending load caused by the trust force.

![Fig 29 Experimental analysis on PAR](image)

<table>
<thead>
<tr>
<th>Strain Gauge 1</th>
<th>$\varepsilon_{\text{max}}$</th>
<th>$\sigma_{\text{max}}$ (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain Gauge 1</td>
<td>5</td>
<td>$7.3 \times 10^3$</td>
</tr>
<tr>
<td>Strain Gauge 2</td>
<td>285</td>
<td>$4.16 \times 10^5$</td>
</tr>
</tbody>
</table>

Table 6: Experiment results for PAR;

$E_{\text{plywood}} = 1.46 \times 10^9$ Pa

Again, the strain values indicated on the strain indicator shows a maximum value only at the initial stages of the test. This is due to the depletion of the power supplied to the
motors over time as experienced in the case of the engine mount. Readings of strain
gauge 1 shows that the stress value, \( \sigma \) Strain Gauge 1 on the PAR structure due to the weight
of the motors is close to that calculated in FEA. However strain gauge 2 provide values
of \( \sigma \) Strain Gauge 2 slightly lower than that shown in FEA (Appendix VI). This can be again
due to losses in wiring and a drop in efficiency of the motors that result in a lower trust
force provided.

5.1.4 Wing

Static loading is done on the wing to simulate conditions during flight. As the wing
should carry the overall estimated weight of the craft of 2 kg, a load of 1 kg is applied on
each wing by mean of weights. As both the spars of the wing are designed to take the
bending loads due to the lift force, linear foil strain gauges are placed on each spar to
obtain the bending stress values it might be undergoing.

![Fig 30 Placement of strain gauges on wing](image)

![Fig 31 Experimental analysis on Wing](image)

<table>
<thead>
<tr>
<th></th>
<th>( \varepsilon ) (( \mu ))</th>
<th>( \sigma ) (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain Gauge 3</td>
<td>4144</td>
<td>6.05 x 10^{6}</td>
</tr>
<tr>
<td>Strain Gauge 4</td>
<td>321</td>
<td>3.94 x 10^{7}</td>
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</tbody>
</table>

Table 7: Experiment results for wing;

\( E_{\text{plywood}} = 1.46 \times 10^{9} \) Pa  \( E_{\text{Crod}} = 122.7 \times 10^{9} \) Pa
5.1.5 Horizontal Tail

The lifting tail configuration for the horizontal tail unit is designed to generate 400g of lift force. As the horizontal tail is fixed to the vertical fin in the middle section of the tail, two loads of 200g each, is placed on each side of the tail as shown in figure 1 below. A linear foil strain gauge was placed on the spar to determine the strain value when it was undergoing bending.

![Fig 32 Strain gauge on spar of tail](image1)
![Fig 33 Experimental analysis on tail](image2)

<table>
<thead>
<tr>
<th>Table 8: Experiment results for horizontal tail;</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{plywood}} = 1.46 \times 10^9 \text{ Pa}$</td>
</tr>
<tr>
<td>$\varepsilon$ (µ)</td>
</tr>
<tr>
<td>$\sigma$ (Pa)</td>
</tr>
</tbody>
</table>

The results of the wing and the horizontal tail obtained differ from that of the one calculated in FEA (Appendix VI). This is mainly due to the assumption that the resultant lift force acts at half the span of both the wing and horizontal tail. In the analysis done using COSMO Works, pressure distribution over the wing and tail is obtained and input from COSMO Flow. This would give a resultant lift force distribution similar to the one seen in fig 2. Where higher lift forces are experienced at the portion of the wing nearer to the fuselage (nearer to vertical fin in horizontal tail’s case) and the resultant lift force would act nearer to the fix position of the wing/horizontal tail. This explains for the
slightly larger in magnitude of the stress values on the spars of the wing and tail this experiment.

5.1.6 Vertical Fin

Along with the horizontal tail, the vertical fin is tested to obtain the strain values when subjected to the lift force of 400g by the tail. As seen in section 5.1.5, weights are placed on the horizontal tail to simulate the 400g of lift force. The vertical fin would thus undergo a tensile force due to this lift force and a bending force at its base. A linear strain gauge is place on the vertical fin to determine the tensile force, while another is placed on the base to obtain the stress value due to the bending load.

Table 9: Experiment results for vertical fin;

<table>
<thead>
<tr>
<th></th>
<th>$\varepsilon$ ($\mu$)</th>
<th>$\sigma$ (Pa)</th>
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<tbody>
<tr>
<td>Strain Gauge 5</td>
<td>413</td>
<td>$6.03 \times 10^5$</td>
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<tr>
<td>Strain Gauge 6</td>
<td>404</td>
<td>$8.73 \times 10^4$</td>
</tr>
</tbody>
</table>

5.2 Final weight breakdown

The designed parts are fabricated under strict control to ensure that the manufactured parts do not exceed the weight estimated initially. Appendix VII shows the final measured weight of the individual components.

5.3 Determination of Center of Gravity

After the fabrication of the craft the position of center of gravity (C.G.) needs to be determined to ensure that the C.G. of the craft is not positioned at undesirable areas.
this experiment, the battery is not included, so as to allow for the variation of the position of C.G. to the exact designed position. This final positioning of the C.G. is done by colleague Mr. Jonathon Quah Yong Seng (AM93).

The experimental setup, which is used to determine the position of the WIG craft C.G., is as shown in fig 35, 36 and 37. The WIG craft is hinged at point A and is only allowed to rotate in a 2D plane. A force is applied at a known position of the WIG craft by using a spring balance. The magnitude of this applied force and the resulted angle of tilt due to this force is read off the scale of the spring balance and protractor. Subsequently this experiment was repeated for another force value. The C.G. position in the x, y and z directions can then be determined by solving the 3 equations formed using simple geometry and taking moments about point A.

Fig 35 Schematics of experimental Setup
5.3.1 Longitudinal direction

\[ F(\text{X}_{\text{applied}}) = M_{\text{wig}}[x \cos(\alpha_{\text{applied}})] \]

\[ X_{\text{c.g.}} = x + Z_{\text{c.g.}} \tan(\alpha_{\text{applied}}) + X_{\text{hinge}} \]

\[ X_{\text{c.g.}} = Z_{\text{c.g.}} / \tan(\alpha_{\text{initial}}) \]

\[ X_{\text{c.g.}} = \frac{F(\text{X}_{\text{applied}})}{[1 - \tan(\alpha_{\text{initial}})\tan(\alpha_{\text{applied}})]M\cos(\alpha_{\text{applied}})} - X_{\text{hinge}} \]

**Figure 36**: setup to determine \( X_{\text{c.g.}} \) of WIG craft

\[ X_{\text{hinge}} = 30.4 \text{cm}, \quad M_{\text{wig}} = 1.377 \text{kg}, \quad \alpha_{\text{initial}} = 8^\circ \]

<table>
<thead>
<tr>
<th>( F ) (N)</th>
<th>( X_{\text{applied}} ) (cm)</th>
<th>( \alpha_{\text{applied}} ) (°)</th>
<th>( X_{\text{c.g.}} ) (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>42.0</td>
<td>68</td>
<td>33.3</td>
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<td>9</td>
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<td>56</td>
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</tr>
<tr>
<td></td>
<td>Average</td>
<td></td>
<td>33.4</td>
</tr>
</tbody>
</table>

**Table 10**: Results of position of C.G. in the longitudinal direction

5.3.2 Lateral direction

\[ F(\text{Y}_{\text{applied}}) = M_{\text{wig}}[y \cos(\theta_{\text{applied}})] \]

\[ Y_{\text{c.g.}} = y + Z_{\text{c.g.}} \tan(\theta_{\text{applied}}) - Y_{\text{hinge}} \]

\[ Y_{\text{c.g.}} = Z_{\text{c.g.}} / \tan(\theta_{\text{initial}}) \]

\[ Y_{\text{c.g.}} = \frac{F(\text{Y}_{\text{applied}})}{[1 - \tan(\theta_{\text{initial}})\tan(\theta_{\text{applied}})]M\cos(\theta_{\text{applied}})} - Y_{\text{hinge}} \]

**Figure 37**: setup to determine \( Y_{\text{c.g.}} \) of WIG craft
\[ Y_{\text{hinge}} = 1.5 \text{cm}, \quad M_{\text{wig}} = 1.377, \quad \theta_{\text{initial}} = 5^\circ \]

<table>
<thead>
<tr>
<th>F (N)</th>
<th>( Y_{\text{applied}}(\text{cm}) )</th>
<th>( \theta_{\text{applied}}(^\circ) )</th>
<th>( Y_{\text{c.g.}}(\text{cm}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>29.4</td>
<td>74</td>
<td>55.3</td>
</tr>
<tr>
<td>6.5</td>
<td>30.6</td>
<td>70</td>
<td>55.1</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td></td>
<td>55.2</td>
</tr>
</tbody>
</table>

Table 11: Results of position of C.G. in the lateral direction

5.3.3 Vertical direction

\[ Z_{\text{c.g.}} = Y_{\text{c.g.}} \tan(\theta_{\text{initial}}) \]

\[ Z_{\text{c.g.}} = 33.4 \tan 8^\circ \]

\[ = 4.69 \text{ cm} \]

The results show that the WIG Craft C.G. in the lateral direction does not directly lie on the line of symmetry of the craft. This is partially due to the variation of density of the raw materials used resulting in the right wing being slightly heavier than the left, as a similar dimension does not render similar weight. However it is not a concern as it is not too far off from the line of symmetry and it can be easily rectified by positioning the battery slight to the left of the WIG craft.
Chapter 6 Flight Testing

6.1 1st Prototype

The figure on the left shows the 1st prototype that was designed and fabricated. Flight test results show that the craft experienced too much hydrodynamic drag for the craft to gain enough speed. The wing is also mounted too high for the PAR to be effective. In addition, the wings are not secured tight enough to restrict it from moving.

Following prototype 1, weight reduction was done to the wing, vertical fin and horizontal tail by cutting the number of ribs used in the wing and changing the material for the vertical fin to balsa wood. The wings were also mounted lower and the addition of 1 screw on each side of the wing was used to further tighten the wing. Results improved dramatically thereafter, with the PAR being effective and the wings being fixed tightly in place.

However the craft still experiences too much hydrodynamic drag which slows down the craft, such that there is not enough lift generated for the craft to take off completely. This is also due to the result of the reduction of ribs, which caused the wing skin to lose its designed shape. Besides, the joint between the vertical fin and horizontal tail is not strong enough to stabilize the horizontal tail, such that the horizontal tail plane is allowed to move during flight test, which is undesirable.
6.3 3rd Prototype

The problem of maintaining the shape of the aerofoil in the wing due to the reduction in ribs was immediately rectified by the addition of stringers. This prevents the foil paper from sagging, maintaining the desired shape of the aerofoil. The vertical fin was also redesigned to have a large horizontal platform for the horizontal tail to rest upon, fixing the horizontal tail into place.

Flight test results of this final prototype show the WIG craft being structurally stable and successfully off the water, demonstrating ground effect. Besides being able to operate on water, the craft is also able to work on land, making it amphibious.
Chapter 7 Conclusion

The objectives of the project were met. In conclusion, the project has successfully accomplished the design, analysis and fabrication of the structures of a working small scale WIG craft. This was made possible due to the successful integration with other aspects of the craft done by fellow colleagues. Aerodynamics by Mr. Ng Geok Hean (AM90), hydrodynamics and propulsion by Mr. Toh Boon Whye (AM92) and stability and control by Mr. Quah Yong Seng Jonathon (AM93)

In the design phase after the general shape of the WIG craft is determined by mainly non-structural considerations, the structural aspect of the craft is designed, taking into account the loads that it will encounter. The design is then subsequently modeled using the CAD software Solidworks and structural analysis is done with the aid of its bundled software Cosmo Works and Cosmo Flow. Together with theoretical calculations, the WIG craft is analyzed structurally to prevent failure during operation.

In the analysis carried out, the highest stresses experienced in the WIG craft is found to be at the root of the wing, at the region on the spars closest to the fuselage when the velocity is above 2m/s. This maximum stress increases with the speed of the craft, and is established by the relation $\sigma_{\text{max}} = 0.1 \times V^2$ MPa (for $2 \text{m/s} \leq V \leq 10 \text{m/s}$). At velocities lower than 2m/s, the maximum stress is found to be at the engine mount whereby $\sigma_{\text{max}} = 9.05$ MPa (for $V \leq 2 \text{m/s}$). At the maximum allowed speed of 10m/s of the craft, the overall aircraft minimum safety factor is designed to be at a value of 2,
A modular design is also designed for. The modular WIG can be dismantled into 10 units when not in operation to allow for easy maintenance, construction and transportation. It also allows for easier modifications of the units due to improvements that may be made during the course of the project.

Structural testing is also done on the fabricated craft to verify the calculations done during the analysis phase. Due to the small size of the WIG craft and limitations in equipment, static loading is done instead on the craft to obtain the stress values on the craft during flight. These values, obtained with the use of linear foil strain gauges were compared to values obtained in CAE.

Numerous flight tests were then done in 2 different locations: MPSH 2 at SRC and a pond at West Coast park. In the flight tests, results show that the fabricated WIG craft was able to demonstrate the concept of ground effect on both hard ground and water, making it a very versatile remotely pilot vehicle.

The plans for the designed WIG vehicle is also drawn and attached at the last section of this thesis.
Chapter 8: Recommendations

Future recommendations for the WIG craft would include:

a) Looking into the possibility of replacing the wing with foldable flat plates to allow for even easier maintenance of the WIG Craft. A foldable flat plate that folds to reduce the effective projected area also allows for the WIG craft to be kept easily for transportation. However, the challenge here would be to ensure that the wing does not fold up and is sufficiently stiff during operation and at the same time strong enough, particularly at the hinges, to prevent structural failure of the WIG craft.

b) To add another mode to operation of the craft, which is to fly stably like an aircraft without ground effect whenever needed. As WIG crafts are stealth to radar detections due to the low altitude they travel, an unmanned WIG craft allows for stealth surveillance in enemy’s territory, particularly along the coastline. To add another mode of operation of flying like an aircraft allows it to overcome obstacles more easily in friendly territory before going into ground effect near enemy’s ground. This would reduce the effective operation time as time is saved in traveling to targeted areas. Besides, it also allows for greater obstacle avoidance capabilities when encountered with tightly congested areas.
References


Appendix
Appendix I

Estimated weight of components

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<th>Component</th>
<th>Number Used</th>
<th>Weight</th>
<th>Total Weight</th>
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<tbody>
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<td>70g</td>
<td>210g</td>
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<tr>
<td>7 ½ in Propellers</td>
<td>2</td>
<td>10g</td>
<td>20g</td>
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<tr>
<td>8 in Propellers</td>
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<td>10g</td>
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<td>Servos</td>
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<td>100g</td>
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<tr>
<td>Balsa Wood</td>
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<tr>
<td>Carbon Rod</td>
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<tr>
<td>Air Foil Paper</td>
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<td>100g</td>
<td>100g</td>
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## Appendix II

### Material selection

<table>
<thead>
<tr>
<th>Materials</th>
<th>Balsa wood</th>
<th>Birch Aircraft Plywood</th>
<th>Polystyrene</th>
<th>Fiberglass</th>
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<td>Weight</td>
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<td>**</td>
<td>***</td>
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<td>Strength</td>
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<td>*****</td>
<td>**</td>
<td>*****</td>
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<td>Density</td>
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<td>Waterproof</td>
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<td>**</td>
<td>***</td>
<td>*****</td>
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<tr>
<td>Ease of fabrication</td>
<td>*****</td>
<td>****</td>
<td>**</td>
<td>*</td>
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<tr>
<td>Stiffness</td>
<td>***</td>
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</table>
Appendix III

Types of glue tested:

- Epoxy
- Cyanoacrylate glue
- Wood glue
Appendix IV

Material Properties

Size of balsa wood specimen = 50 x 25 x 3 (length x breadth x thickness)

Elastic Modulus of Balsa wood used $E_{\text{balsa}} = \frac{\sigma}{\varepsilon}$

\[
= \frac{(400 - 201)/(0.025 \times 0.003)}{(0.490 - 0.233) / 50}
\]

= 216 MPa

From results, specimen starts to yield at 426 N

Therefore, Yield strength = $\frac{426}{(0.025 \times 0.003)}$

= 5.68 MPa
Balsa wood - against the grain (tangential)

Size of balsa wood specimen = 50 x 25 x 3 (length x breath x thickness)

Elastic Modulus of Balsa wood used \( E_{\text{balsa}} = \frac{\sigma}{\varepsilon} \)

\[ \frac{30.19 - 5.369}{(0.025 \times 0.003)} \frac{3.032}{(0.833 - 0.115) / 50} = 23.1 \text{ MPa} \]

From results, specimen starts to yield at 40 N

Therefore, Yield strength = \( \frac{40}{(0.025 \times 0.003)} \)

\[ = 0.533 \text{ MPa} \]
Size of plywood specimen = 50 x 15 x 2 (length x breath x thickness)

Elastic Modulus of plywood used $E_{\text{plywood}} = \frac{\sigma}{\varepsilon}$

$= \frac{(401-104)/(0.015\times0.002)}{(0.433 - 0.0936) / 50}$

$= 1.46 \text{ GPa}$

From results, specimen starts to yield at 414 N

Therefore, Yield strength $= \frac{414}{(0.015\times0.002)}$

$= 13.8 \text{ MPa}$
Carbon rod properties

Grade: GR-CFR

Manufacturer: Graphite, LLC
Description: Manufactured by pulling carbon fiber and vinylester through a die of the desired cross section to form a densely reinforced carbon composite to provide excellent tensile, compressive, and transverse strength.

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<th>PROPERTY</th>
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<th>METRIC VALUE</th>
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<tr>
<td>Resin</td>
<td>Vinylester</td>
<td></td>
</tr>
<tr>
<td>Fiber Type</td>
<td>.33 m.s.i. Carbon</td>
<td></td>
</tr>
<tr>
<td>Composite Type</td>
<td>Unidirectional Orientation</td>
<td></td>
</tr>
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<td>Tensile Strength</td>
<td>200000 psi</td>
<td>1379.0 mpa</td>
</tr>
<tr>
<td>Flexural Strength</td>
<td>230000 psi</td>
<td>1595.0 mpa</td>
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<tr>
<td>Flexural Modulus</td>
<td>17.8 msi.</td>
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<tr>
<td>Shear Strength</td>
<td>9500 psi</td>
<td>65.5 mpa</td>
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<tr>
<td>Fiber Volume</td>
<td>62 %</td>
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<tr>
<td>Density</td>
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<td>1.49 g/cm^{-3}</td>
</tr>
<tr>
<td>Diameter Tolerance</td>
<td>+.003 / -.003 &quot;</td>
<td>+.008 / -.008 cm</td>
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Appendix V

Theoretical Calculations

Yield strength of wrought stainless steel = 241MPa
Shear yield strength of wrought stainless steel = 139MPa
Yield strength of Birch Aircraft plywood = 13.8 MPa
Yield strength of Balsa wood (longitudinal) = 5.68 MPa
Yield strength of Balsa wood (tangential) = 0.533 MPa
Yield strength of Brass = 250MPa
Minimum designed safety factor requirement = 2

4.2.1.1 fuselage

a) Stainless steel screws connecting hinge to fuselage (PAR)

Cross sectional area of screw in plane into paper undergoing bearing stress

\[ = 3 \times 5 \times 10^{-6} \]

\[ = 15 \times 10^{-6} \text{ m}^2 \]

Trust of two engines \( F_i \) = 2.6 x 2

\[ = 5.2 \text{ N} \]

Trust load carried by one screw = 5.2 / 3

\[ = 1.73 \text{ N} \]

Bearing stress on each screw = 1.73 / \((15 \times 10^{-6})\)

\[ = 1.15 \times 10^5 \text{ Pa} \]

Safety factor > 2

Bearing stress on fuselage = 1.15 x 10^5 Pa

Safety factor > 2
b) Spars slotted into fuselage

**Wooden spar**

Lift force carried by wooden spar = 0.5 * 9.81  
= 4.905

Cross sectional area of wooden spar $A_{woodspar}$ undergoing bearing stress  
= $b_{woodspar} \times w_{woodspar}$  
= 4.5 x 9 x 10^{-6}  
= 4.05 x 10^{-5} m²

Bearing stress on fuselage = 4.905 / (4.05 x 10^{-5})  
= 1.21 x 10^{5} Pa

Safety factor > 2

**Carbon Rod**

Lift force carried by carbon rod spar = 4.905

Cross sectional area of carbon rod spar $A_{rod}$ undergoing bearing stress  
= $d_{outer} \times w$  
= 7 x 9 x 10^{-6}  
= 6.3 x 10^{-5} m²

Bearing stress on fuselage = 4.905 / (6.3 x 10^{-5})  
= 0.78 x 10^{5} Pa

Safety factor > 2

c) Stainless steel screws vertical fin to fuselage

Cross sectional area of screw in plane into paper undergoing bearing stress  
= 3 x 7 x 10^{-6}  
= 21 x 10^{-6} m²
Trust of rear engine \( (F_r) = 2.6 \text{ N} \)

Trust load carried by one screw = \( \frac{2.6}{6} \)

= 0.43 N

Bearing stress on each screw = \( \frac{0.43}{(21 \times 10^{-6})} \)

= \( 2.05 \times 10^4 \text{ Pa} \)

Safety factor > 2

Bearing stress on fuselage = \( 2.05 \times 10^4 \text{ Pa} \)

Safety factor > 2

4.2.1.2 Engine Mount

a) Stainless steel screws holding motor mount to vertical fin

The trust load is shared among the 3 screws

Trust of engine: \( (F_i) = 2.6 \text{ N} \)

Trust load carried by one screw = \( \frac{2.6}{3} \)

= 0.867N

Cross sectional area of screw in plane into paper undergoing bearing stress

= \( 4 \times 3 \times 10^{-6} \)

= \( 12 \times 10^{-6} \text{ m}^2 \)

Bearing stress on each screw = \( \frac{0.867}{(12 \times 10^{-6})} \)

= \( 72.3 \times 10^3 \text{ Pa} \)

Safety factor >2

Cross sectional area of screw in plane of paper = \( \Pi \times 3^2 /4 \times 10^{-6} \)

= \( 7.07 \times 10^{-6} \text{ m}^2 \)

Shear stress on each screw = \( \frac{0.867}{(7.07 \times 10^{-6})} \)
= 122 x 10^3 Pa

Safety factor > 2

b) Stainless steel screws holding motor

The trust load is shared between 4 screws

Trust of engine: \( F_t \) = 2.6 N

Trust load carried by one screw = \( 0.265 \times 9.81 / 4 \)

= 0.65 N

Cross sectional area of screw in plane into paper undergoing bearing stress

\( = 3 \times 1 \times 10^{-6} \)

\( = 3 \times 10^{-6} \text{ m}^2 \)

Bearing stress on each screw = \( 0.65 / (3 \times 10^{-6}) \)

= 4.17 \times 10^5 \text{ Pa}

Safety factor > 2

Cross sectional area of screw in plane of paper = \( \pi \times 3^2 / 4 \times 10^{-6} \)

= 7.07 \times 10^{-6} \text{ m}^2

Shear stress on each screw = \( 0.65 / (7.07 \times 10^{-6}) \)

= 0.92 \times 10^5 \text{ Pa}

Safety factor > 2

c) Stainless steel motor holder

Bearing stress on motor holder = \( 0.65 / (3 \times 10^{-6}) \)

= 2.17 \times 10^5 \text{ Pa}

Safety factor > 2
d) Plywood

Bearing stress on plywood due to screws holding engine mount to fin
= 72.3 x 10³ Pa
Safety factor > 2

Bearing stress on plywood due to screws holding engine to engine mount
= 0.65 / (12 x 10⁻⁶)
= 0.54 x 10⁵ Pa
Safety factor > 2

4.2.1.3 PAR

a) Stainless steel screws holding motor

The trust load is shared between 2 screws

Trust of engine: \( F_t = 2.6 \) N

Trust load carried by one screw = \( 2.6 / 2 \)

= 1.30 N

Cross sectional area of screw in plane into paper undergoing bearing stress
= 3 x 1 x 10⁻⁶
= 3 x 10⁻⁶ m²

Bearing stress on each screw = \( 1.30 / (3 x 10⁻⁶) \)

= 4.33 x 10⁵ Pa

Safety factor > 2

Cross sectional area of screw in plane of paper = \( \Pi x 3^2 / 4 x 10⁻⁶ \)

= 7.07 x 10⁻⁶ m²
Shear stress on each screw = \( \frac{1.30}{(7.07 \times 10^{-6})} \)

\[ = 1.84 \times 10^5 \text{ Pa} \]

Safety factor > 2

b) Stainless steel motor holder

Bearing stress on motor holder = \( \frac{1.30}{(3 \times 10^{-6})} \)

\[ = 4.33 \times 10^5 \text{ Pa} \]

Safety factor >2

c) Stainless steel screws connecting PAR to hinge

The trust load is shared among the 3 screws

Trust of two engines = \( 2.6 \times 2 \)

\[ = 5.2 \text{ N} \]

Trust load carried by one screw = \( \frac{5.2}{3} \)

\[ = 1.73 \text{ N} \]

Cross sectional area of screw in plane into paper undergoing bearing stress

\[ = 3 \times 1 \times 10^{-6} \]

\[ = 3 \times 10^{-6} \text{ m}^2 \]

Bearing stress on each screw = \( \frac{1.73}{(3 \times 10^{-6})} \)

\[ = 0.577 \times 10^5 \text{ Pa} \]

Safety factor >2

Cross sectional area of screw in plane of paper = \( \Pi \times \frac{3^2}{4} \times 10^6 \)

\[ = 7.07 \times 10^{-6} \text{ m}^2 \]

Shear stress on each screw = \( \frac{1.73}{(7.07 \times 10^{-6})} \)

\[ = 2.45 \times 10^5 \text{ Pa} \]
Safety factor > 2

d) Plywood

Cross sectional area of plywood in plane into paper undergoing bearing stress

\[ = 3 \times 4 \times 10^{-6} \]

\[ = 12 \times 10^{-6} \text{ m}^2 \]

Bearing stress due to bolts holding motor = \( \frac{1.30}{12 \times 10^6} \)

\[ = 1.08 \times 10^5 \text{ Pa} \]

Safety factor > 2

Bearing stress due to bolts connecting PAR to hinge = \( \frac{1.73}{12 \times 10^6} \)

\[ = 1.44 \times 10^5 \text{ Pa} \]

Safety factor > 2

e) Hinge

Cross sectional area of hinge in plane into paper undergoing bearing stress

\[ = 3 \times 1 \times 10^{-6} \]

\[ = 3 \times 10^{-6} \text{ m}^2 \]

Bearing stress due to bolts connecting PAR to hinge = \( \frac{1.73}{3 \times 10^6} \)

\[ = 5.77 \times 10^5 \text{ Pa} \]

Safety factor > 2

Bearing stress due to bolts connecting PAR to fuselage = 5.77 \( \times 10^5 \) Pa

Safety factor > 2

f) Stainless steel screws connecting hinge to fuselage

Trust load carried by one screw = 1.73 N

Cross sectional area of screw in plane into paper undergoing bearing stress
Bearing stress on each screw = \( 1.73 / (3 \times 10^{-6}) \)
\[= 0.577 \times 10^5 \text{ Pa} \]
Safety factor > 2

Cross sectional area of screw in plane of paper = \(7.07 \times 10^{-6} \text{ m}^2\)
Shear stress on each screw = \(2.45 \times 10^5 \text{ Pa}\)
Safety factor > 2

### 4.2.1.4 Vertical Fin

a) Stainless steel screws holding motor mount to vertical fin

Cross sectional area of fin in plane into paper undergoing bearing stress
\[= 5 \times 3 \times 10^{-6} \]
\[= 15 \times 10^{-6} \text{ m}^2 \]
Bearing stress on each screw = \(0.867 / (15 \times 10^{-6})\)
\[= 57.8 \times 10^3 \text{ Pa} \]
Safety factor > 2

Bearing stress on vertical fin = \(57.8 \times 10^3 \text{ Pa}\)
Safety factor > 2

b) Stainless steel screws holding vertical fin to fuselage

Cross sectional area of stainless steel screw in plane into paper undergoing bearing stress due to trust load of engine = \(5 \times 3 \times 10^{-6} \)
\[= 15 \times 10^{-6} \text{ m}^2 \]
Bearing stress on each screw = \(0.433 / (15 \times 10^{-6})\)
$= 28.9 \times 10^3 \text{ Pa}$

Safety factor > 2

Bearing stress on vertical fin $= 28.9 \times 10^3 \text{ Pa}$

Safety factor > 2

### 4.2.1.5 Wing

a) Bending stress on carbon rod $\sigma_{yy} = \frac{M_y}{I_{yy}}$

Bending moment $M = 0.5 \times 9.81 \times 0.25$

$= 1.23 \text{ Nm}$

Dimensions of carbon rod: Inner diameter $d_1 = 0.0025 \text{ m}$

Outer diameter $d_2 = 0.006 \text{ m}$

$I_{yy} = \pi \left( d_2^4 - d_1^4 \right) / 64$

$= \pi \left( 0.0074^4 - 0.00254^4 \right) / 64$

$= 1.16 \times 10^{-10} \text{ m}^4$

Maximum bending stress $\sigma_{yy} = \frac{1.23 \times 0.0035}{1.16 \times 10^{-10}}$

$= 3.71 \times 10^7 \text{ Nm}^{-2}$

b) Cross sectional area of carbon rod $A_{rod} = \pi \left( d_2^2 - d_1^2 \right) / 4$

$= \pi \left( 0.0072^2 - 0.0025^2 \right) / 4$

$= 3.36 \times 10^{-5} \text{ m}^2$

Shear stress on carbon rod $\tau = \frac{F}{A_{rod}}$

$= 0.5 \times 9.81 / (3.36 \times 10^{-5})$

$= 1.46 \times 10^5 \text{ Nm}^{-2}$

Safety factor > 2
c) Bending stress on wooden spar $\sigma_{yy} = \frac{M_y}{I_{yy}}$

Bending moment $M = 0.5 \times 9.81 \times 0.25$

$= 1.23 \text{ Nm}$

$I_{yy} = \frac{h_{woodspar} b_{woodspar}^3}{12}$

$= \frac{(4.5 \times 10^{-3})^3 \times (14 \times 10^{-3})}{12}$

$= 1.28 \times 10^{-9} \text{ m}^4$

Maximum bending stress $\sigma_{yy} = 1.23 \times 0.007 / (1.28 \times 10^{-9})$

$= 6.73 \times 10^6 \text{ Nm}^{-2}$

Safety factor $= \frac{13.8}{6.73}$

$= 2$

d) Cross sectional area of wooden spar $A_{woodspar} = b_{woodspar} \times h_{woodspar}$

$= 4.5 \times 14 \times 10^{-6}$

$= 6.3 \times 10^{-5} \text{ m}^2$

Shear stress on carbon rod $\tau = \frac{F}{A_{woodspar}}$

$= \frac{0.5 \times 9.81}{(6.3 \times 10^{-5})}$

$= 7.8 \times 10^4 \text{ Nm}^{-2}$

Safety factor $> 2$

4.2.1.6 Horizontal Tail

a) Bending stress on wooden spar $\sigma_{yy} = \frac{M_y}{I_{yy}}$

Bending moment $M = 0.1 \times 9.81 \times 0.1$

$= 98.1 \times 10^{-3} \text{ Nm}$

$I_{yy} = \frac{h_{woodspar} b_{woodspar}^3}{12}$

$= \frac{(5 \times 10^{-3})^3 \times (5 \times 10^{-3})}{12}$
= 5.21 x 10^{-11} m^4

Maximum bending stress \( \sigma_{yy} = 98.1 \times 10^{-3} \times 2.5 \times 10^{-3} / (5.21 \times 10^{-11}) \)

= 4.71 \times 10^6 \text{ Nm}^{-2}

Safety factor = 13.8 / 4.71

= 3
Appendix VI

CAE - Analysis results

Fuselage

Fuselage – Stress Plot (With rudder at 0 °)

Fuselage – Displacement Plot (With rudder at 0 °)
Fuselage – displacement Plot (With rudder at maximum angle of 20 °)

Engine Mount

Engine Mount – displacement plot
Power Augmentation Ram Arm (PAR)

Stress Plot – Isometric View

Stress Plot – Rear View

Displacement Plot – Isometric View
Vertical Fin

![Vertical Fin – displacement plot](image1)

Wing

![Wing – Displacement Plot](image2)
Horizontal Tail

Horizontal Tail – Displacement Plot
## Final measured weight of components

<table>
<thead>
<tr>
<th>Component</th>
<th>Actual Weight (kg)</th>
<th>Percentage Weight (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motors, servos, servo mount, receiver</td>
<td>0.142</td>
<td>9.5</td>
</tr>
<tr>
<td>Propellers</td>
<td>0.036</td>
<td>2.4</td>
</tr>
<tr>
<td>Batteries</td>
<td>0.113</td>
<td>7.6</td>
</tr>
<tr>
<td>PAR</td>
<td>0.197</td>
<td>13.2</td>
</tr>
<tr>
<td>Vertical Fin with motor connected</td>
<td>0.170</td>
<td>11.4</td>
</tr>
<tr>
<td>Horizontal tail</td>
<td>0.063</td>
<td>4.2</td>
</tr>
<tr>
<td>Fuselage</td>
<td>0.332</td>
<td>22.4</td>
</tr>
<tr>
<td>Wings</td>
<td>0.437</td>
<td>29.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.49</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>
Drawings
Drawing 3 - Power Augmentation Ram Arm