Hydrodynamic Impact Analysis and Testing of an Unmanned Aerial Vehicle

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HYDRODYNAMIC IMPACT ANALYSIS AND TESTING OF AN UNMANNED AERIAL VEHICLE

by

Isabel Bird

A Thesis Submitted to the College of Engineering Department of Mechanical Engineering
In Partial Fulfillment of the Requirements for the Degree of Master of Science in Mechanical Engineering

Embry-Riddle Aeronautical University
Daytona Beach, Florida
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This thesis was prepared under the direction of the candidate’s Thesis Committee Chair, Dr. Patrick Currier and Thesis Committee Member Dr. Charles Reinholtz. It was submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering.

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Abstract

Analysis and testing have been conducted to assess the feasibility of a small UAV that can be landed in the water and recovered for continued use. Water landings may be desirable in a number of situations, for example when testing UAVs outside of the territorial waters of the US to avoid violating FAA regulations. Water landings may also be desirable when conducting surveillance missions in marine environments. Although the goal in landing is to have the UAV lightly set down on the water, rough seas or gusty winds may result in a nose-in landing where the UAV essentially impacts the surface of the water. The tested UAV is a flying wing design constructed of expanded polypropylene foam wings with a hollowed out center-section for the avionics. Acceleration data was collected by means of LIS331 3-axis accelerometers positioned at five locations, including the wingtips. This allowed conclusions to be drawn with respect to the loads experienced on impact throughout the airframe. This data was also used to find loads corresponding to the maximum decelerations experienced during impact. These loads were input into a finite element analysis model of the wing spars to determine stress in the wing spars. Upon impact, the airframe experienced high-frequency oscillation. Surprisingly, peak accelerations at the wingtips were observed at up to 15g greater than corresponding accelerations at the center of the fuselage.
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Chapter 1

Introduction

The concept of aerial surveillance has been around since before the first Airplanes were in flight, with the first kite assisted aerial photograph being taken in 1882 with a camera mounted to a kite and a long string attached to control the shutter[3]. The first aerial photograph taken on a manned flight was even earlier in 1858 when Gaspar Felix Tournachon captured images from a hot air balloon[23]. Aerial photography was quickly adapted for military applications by the Union Army in the Civil War and by the Americans in the Spanish-American war of 1898[17] and since then Aerial surveillance has developed quite significantly with the first reconnaissance Unmanned Aerial Vehicles (UAVs) being developed in the 1960s. A derivative of the Ryan Firebee (initially a target drone), the reconnaissance UAV known as a lightening bug was used to spy on China, North Korea and Vietnam.

Modern UAVs, although primarily used in military applications, are now branching out into other applications such as commercial fishing and natural observation. The lower budgets of these applications and different operating conditions, however, require a different sort of UAV to be developed to make it a viable option. Such a UAV should be designed to be cost effective while maintaining durability within its operating conditions. It is also necessary to take into account the fact that once in service the UAVs are likely to be operated by controllers with minimal training and are likely to undergo various rough landings on multiple terrains.
CHAPTER 1. INTRODUCTION

The Pelican project is a research project to develop a UAV that is capable of landing at sea and being recovered from the water for re-use. Smooth landings at sea are an unlikely situation due to waves forming and little research has been done into the loads experienced when a UAV impacts with water. This thesis aims to provide a better understanding of the structural behavior of a UAV landing at sea.

1.1 Purpose Statement

The purpose of this study was to analyze the impact of a UAV on water. This analysis would allow for an understanding of the viability of a UAV that can be reused after a crash landing on water. This analysis is part of a larger project to develop a UAV that is capable of launching from land and landing in water with the option of retrieving and reusing the UAV.

In order to be able to design a suitable UAV an already existing UAV was used in testing so that the effects of impact could be assessed for that structure allowing a new design to be developed in order to account for any issues encountered during the testing and analysis. The initial UAV chosen for testing was the "Zephyr" (developed by RitewingRC).

Figure 1.1: Ritewing Zephyr
CHAPTER 1. INTRODUCTION

This is a basic flying wing design built from Expanded Polypropylene foam (EPP) with carbon fiber and fiberglass wing spars. It was chosen for the reason that the EPP foam makes it likely to be suitable for marine use as it is lightweight, can float on water and is water resistant. The intention is to be able to design a new, waterproof center-section to house the avionics, with wings attached by the wing spars based on the results of the analysis. In order to do so it was important to gather data on the extent of the loading experienced by the wing spars and decide whether they are able to withstand such loads. The initial testing was done using crude methods of waterproofing to keep any avionics from getting waterlogged but the new center-section will be designed such that all avionics will remain protected.

Analysis of the impact was done using experimental data from launching the Zephyr into water and gathering information on the acceleration of the airframe during impact. Following this the data was input into the Finite Element Analysis (FEA) program Ansys and applied to a model of the wing spars currently used with the Zephyr. The Ansys model was used to create a set of design specifications for wing spar fuselage joints to handle the impact loads of a water landing.

1.2 Significance of the Study

Mission time of conventional UAVs is limited by the time required to transit to and from the area of interest. Reconnaissance time can be maximized by removing the need to transit back to a landing zone and instead ditching into the water when power is exhausted. Such applications would require a design that ensures all avionics on board are kept encased in a sealed waterproof fuselage and that is buoyant enough to stay afloat long enough for recovery. The initial idea for this design was one that consisted of foam wings attached to a watertight center section by the wing spars. The water landings, however, are likely to impose severe structural stresses on the airframe especially in choppy conditions and when the operator is unable to achieve a smooth landing. In order to optimize the airframe of the UAV such that it is able to withstand stresses experienced on impact with water, in particular the wing spars which would carry a large proportion of the loading while holding
the wings to the center-section, it is necessary to calculate how extensive the loads on the aircraft are likely to be.

The significance of the study is to measure the accelerations on a plane water landing and then to correlate those results to spar loads in a representative design.
Chapter 2

Review of the Relevant Literature

2.1 UAVs for Natural Observation and Maritime Surveillance

Natural observation using UAVs has been a topic of significant interest, particularly over the past decade. With advances in recent technology a UAV is seen to be a viable alternative to current methods of observation such as sending researchers up in light aircraft. Often aircraft will have to fly at low altitudes in order for researchers to gather usable data. This can be dangerous in a light aircraft. A UAV is able to fly at lower altitudes than a light aircraft and is therefore able to collect more accurate data and is able to do so without any risk to people and without creating significant noise disturbances. UAVs typically cost less to run and can therefore be used for longer periods of time for the same cost as a light aircraft, depending on their endurance, thus allowing for a greater amount of data to be collected. One example of UAVs being considered for surveillance applications is the work of Herwitz et al[13], who researched imaging for agricultural surveillance using UAVs. This project involved using NASA’s Pathfinder-Plus UAV to collect images around a coffee plantation in Kauai. Such images allowed anomalies to be detected in the crop, which could then be found and rectified thanks to the ability to gather the location from clear color images. The Pathfinder plus is a lightweight flying wing that is powered using eight solar-electric motors. It is essentially a larger version of the earlier Pathfinder, which
has been used by NASA to assess it’s capabilities during low-altitude missions. Such tests allowed a demonstration of the aircraft’s suitability for image collection. The use of the Pathfinder Plus for image collection was successful due to its slow flight and its ability to loiter for several hours. The solar powered aspect was concluded to be an effective asset in terms of costs of operation and long endurance.

Horcher and Visser[14] conducted research on natural resource management, which adapted the “Bat III” to collect both still and video imagery for invasive species monitoring. Their design was modular, which made it easier to transport. The modular design was a popular concept for natural observation as often take off and landings must be done from difficult areas to access and the ability to take the airframe apart and fit it into a backpack, for example, would negate many of the transport issues of a non-modular design. During the testing a live video feed was successfully fed back to the base station, however the still image processing was less successful due to various factors such as unsuitable image overlap. A large issue discovered by this report was the expense involved as already available UAV technology is currently very expensive to purchase. The system used cost approximately $42,000 and replacement of the UAV should a crash occur was estimated at $20,000. Also US processing companies were used for mapping, which incurred high costs ranging between $50 and $200 per image. These are expected to decrease in time as UAV image processing becomes more commonplace.

Jones[15] opted for the folding wing design of the “FoldBat” for his thesis on small-unmanned vehicles for wildlife research. The research initially acknowledged that the use of UAVs for surveillance could negate several issues currently experienced with aerial surveys conducted using manned aircraft. UAVs, for example, offer the option of low altitude flight without causing any danger to any person as well as a decrease in operation costs for surveillance. The folding design was intended to make the UAV easy to transport however the design of the wings turned out to be a disadvantage as the operation was intended to be carried out by those with minimal training and would therefore incur imprecise landings. Such landings could result in damage to the wings, which would then be difficult to repair due to the intricacy of the hinge design. Jones suggested that removable wings and modular construction be used in any future testing as the folding wing sacrificed the durability of the aircraft.
Matthew Bennet[7] discussed the development of low cost UAVs for oceanographic research, suggesting that the necessity of water landings meant a low probability of aircraft reuse. This prompted the idea of a disposable, single use type of aircraft in order to minimize expenses. McGill[18] et al also opted for inexpensive UAVs for the application of tracking free-floating icebergs, observing that the current use of helicopters was a complex system in terms of stations and equipment required as well as being cost prohibitive. The UAVs were intended to deliver payloads to the icebergs after which the UAVs were considered expendable and were therefore designed without the expectation that they would be able to land unscathed. This allowed the design of the UAV to be far less expensive than that of a reusable UAV.

2.2 Water-Worthy UAVs

The literature surrounding the waterproofing of aircraft is extensive, with the seaplane concept first being introduced in 1910 by Inventor Henri Fabre[10]. The plane, nicknamed “Le Canard”, took off from water on March 28th and consisted of a skeletal design mounted on three “scientifically designed” floats. The concept of float has since carried over to research into Sea worthy UAVs, an example of this being the “Flying Fish” UAV developed by the University of Michigan. This UAV resembles a small sized modern Sea Plane and is capable of taking off from and landing on water. Pisanich[22] carried out research to develop a similar concept at the NASA Ames Research Center. The approach taken was to develop a small-scale prototype built primarily from Balsa and Plywood, which was reinforced with fiberglass, epoxy paint and a Mylar covering. This aircraft also incorporated a twin hull design to improve water landings and reduce the stress on the wings. The design was considered a success in general as the UAV was able to operate from water, however several of the initial tests resulted in leakages which caused damage to the avionics and required extra measures in waterproofing before further tests could be carried out. This highlighted the difficulties in designing a fully waterproof UAV.
Belik et al[6] presented a similar approach, proffering the idea of a fuselage constructed of a buoyant material and having separators inside the fuselage. These separators created compartments with drainage channels leading to weep holes, allowing minimization of the area of the fuselage that would need to be waterproofed. Bachmayer et al[4], while studying the concept of underwater gliders, suggested the inclusion of an inflatable bladder in the tail cone of the glider. This bladder could bring the glider to surface in order to be retrieved.

Many other ideas for sea-worthy UAVs have also been put forward, such as the idea proposed by Gonçalves-Coelho et al[9] to waterproof all electronics with rubber balloons, Lubricant grease and glue. This waterproofing was tested by submerging the UAV in a waterproof tank for a 24 hour period and no leakages were discovered after this time. The structure was made from EPP to withstand high impact landings and also provide buoyancy in case the UAV were to crash land at sea. Although the method of waterproofing proved successful it was fairly crude as the focus of the project was more on the surveillance aspect of the mission. Such methods of waterproofing would not be suitable for any type of professional venture.

Both Stevenson[25] and Pearson[20] again presented the concept of disposable/semi-disposable structures in their reports. Stevenson’s report on Air launched Autonomous Underwater Vehicles (AUVs) suggested minimizing sub-systems and manufacturing costs
so that the AUV could be considered Semi-disposable. He refers to the number of small sensors, already in the market, for tagging fish and mammals, in order to support his suggestion. He also suggests that if a UAV is to be considered semi-disposable a rechargeable system of batteries would be unnecessary and raise costs. The report theorizes that for a UAV to be designed with the intention of being semi-disposable it is very important to drive costs down considerably.

Pearson presented a paper on the topic of the future of Maritime UAVs in which he reviews many currently existing concepts. Two of these concepts were Northrop Grumman’s Stealthy Affordable Capsule System (SACS) and the Sea Sentry both of which involve storing small UAVS in containers from which they are released. In each case the UAVs are required to be expendable.

### 2.3 Hydrodynamic Impact

#### 2.3.1 Formula Development

In order to better understand the problem of hydrodynamic impact various studies have been carried out using simple shapes such as a sphere or a cone. The limitations of the instrumentation used in early such studies provided difficulties in experimental analysis. Watanabe’s[27] studies into the impact of a cone with water in 1930 and later a sphere involved the use of piezoelectric gauges connected to an oscilloscope. The studies on cones were revisited in 1971 by John Baldwin[5], who then had access to more modern equipment for experimentation. Experiments were carried out to find the vertical deceleration of the cone on impact with water by attaching accelerometers to cones of different weights. Following experimentation, formulae were developed expanding on Von Karmen’s[16] theorems on momentum and added mass to predict deceleration of the cone. On comparison with the experimental results it was gathered that the analytical results were suitable for future predictions. It was also proved that the total added mass constant $K$ as calculated from

\[
K = k + \frac{C_{ds}}{6} (\tan \frac{\theta}{2})^{-1} \pi
\]  

(2.1)
was constant upon wetting of the cone.

Early research into the field of hydrodynamic impact of airborne vehicles was carried out in the 1920's by Theodore Von Karmen. Von Karmen documented the importance of determining the maximum pressure acting on seaplane floats during impact with water, deriving impact formulae for both a wedge-shape under surface and a flat-shape under surface. The calculations were based on the momentum theorem and the assumption of added mass during impact, distributing the momentum at time $t$ between the body and the water, which gives an expression for the total momentum:

$$ M = \frac{W}{g} v + \frac{1}{2} x^2 \rho \pi v $$  \hspace{1cm} (2.2)

For a long plate of width $2x$. Setting this as equal to:

$$ M = \frac{W}{g} v_o $$  \hspace{1cm} (2.3)

Where $v$ is the downward velocity at time $t$ and $v_o$ is the velocity at impact. Defining $v$ as equal to:

$$ \frac{dy}{dt} = tan \alpha \frac{dx}{dt} $$  \hspace{1cm} (2.4)

allowed for derivation of the expression for the force of impact:

$$ P = \frac{W}{g} \frac{d^2y}{dt^2} = \frac{v_o^2 \cot \alpha}{\left(1 + \frac{\gamma x^2}{2W}\right)^3} \rho \pi x $$  \hspace{1cm} (2.5)

($P = \rho F c v_o$ for flat-bottomed)

and the average pressure:

$$ p = \frac{P}{2x} = \frac{\rho v_o^2}{2} \frac{\pi c \cot \alpha}{\left(1 + \frac{\gamma x^2}{2W}\right)^3} $$  \hspace{1cm} (2.6)

($p = \frac{\rho v_o^2}{2} \left(\frac{2c}{g}\right)$ for flat-bottomed)

Where $\alpha$ represents the angle of inclination of the under-surface of the wedge, $\gamma = \rho g$ and $c$ is the speed of sound in the fluid.
For the wedge-shape under surface of the floats pressure would be greatest at the center of the wedge and at the moment of first contact which allows the expression for maximum pressure to be written as

$$p_{\text{max}} = \frac{\rho v_o^2}{2} \pi \cot \alpha$$

(2.7)

Conclusions were made after comparisons of the results of maximum pressure for several downward velocities for both shapes of surface that the flat-bottomed surface caused too great stresses in the struts and bracings although Von Karmen states that pressures experienced by an actual aircraft would be less due to the elastic yielding of the structure when compared to that of the water. He goes on to highlight the importance of combining experimental data with theoretical analysis.

Herbert Wagner[26] was the first to then develop on Von Karmen’s studies in 1932, primarily dealing with both the take-off and landing of seaplanes. In this analysis he accounts for the water movement on impact such as the splash created and the piling up of the water around the intersection between the free surface and the body surface.

Monaghan and Crewe[19] further worked on the development of formulae for Seaplane floats impacting water in 1949. The formulae developed were to estimate the maximum acceleration and the conditions surrounding it, to include time to maximum acceleration and draft at maximum acceleration. The formula for maximum acceleration in this report was

$$\left(\frac{dV_n}{dt}\right)_{\text{max}} = -A_0 K^{1/3} \frac{(V_n^2/g)}{(W/\rho g)^{1/3}}$$

(2.8)

This is assuming main-step landings, no rotation and no chine immersion, where chines are the longitudinal seams which join the sides of the float to the bottom, transmitting the loads from the bottom to the sides. The theoretical value of the maximum acceleration factor ($A_0$) is obtained by the equation of motion

$$A_0 = \frac{3\mu_m^{2/3}}{1 + \mu_m} \left(\frac{\omega_{Tm}}{\omega_{T0}}\right)^2$$

(2.9)
and the associated-mass factor \((K)\) is obtained from the geometry and attitude of the hull or float. The results of these estimations were then compared with that of experimental data conducted by the National Advisory Committee for Aeronautics (N.A.C.A) in their impact basin and were found to be in agreement. The experimental tests were done in model scale using launching tanks so it was necessary to convert the results of these tests to full scale values for comparison.

More recently Zhao and Faltinsen\[29, 11\] compared the results of two different methods for predicting slamming loads on an axisymmetric body upon impact with water with an asymptotic solution and experimental data. The methods under consideration were that of a fully nonlinear solution and a simplified solution based on Wagner’s approach, both of which were solved as initial value problems to include flow separation from the knuckles and bodies with convex shape. The non-linear solution is found for fully non-linear free-surface conditions neglecting gravity and exact body boundary conditions. The simplified solution was a generalization of Wagner’s approach to finding the solution for the piled up water around the intersection between free and body surfaces and obtaining pressure distribution as a function of time. In this case it was generalized to include flow separation. The two theories were compared for pressure distributions based on varying dead-rise angles. These solutions agreed well with each other and were validated by the existing empirical data presented in earlier studies by Zhao and Faltinsen as shown in fig 2.2.
Candy, Kirk and Murrel[8] suggested a non-linear Finite Element method to assess the effect of water impact on a medium weight helicopter. These studies were carried out as a result of the multiple failures of helicopter Emergency Flotation Systems (EFS) in the UK. In order to model the aircraft certain simplifications were employed such as the utilization of a continuous mesh in place of modeling the rivets on the structure as well as representing large mechanical items as point masses. Both Lagrangian and Eulerian approaches were incorporated to model the water. It was discovered that the Eulerian model was the preferred of the two, however the modeling of the impact of the airframe with the water was a relatively new technique and was complex as well as being computationally expensive. Randhawa and Lanakarani[24] also were interested in the Lagrangian vs Eulerian approaches. For their studies they primarily focused on the Lagrangian technique initially and then incorporated a more accurate combined Arbitrary Lagrangian Eulerian method.
Pentecote, Delsart and Vagnot[21] carried out an evaluation of the Smooth Particle Hydrodynamic (SPH) method of water impact simulation on a PUMA helicopter. Initially tests were carried out for rigid cylindrical and triangular bodies before applying the numerical tools to the ditching of a helicopter. The studies on the helicopter ditching were carried out at ONERA using their code Radioss to develop an FE model. Eurocopter provided the Computer-Aided Design (CAD) file for this analysis. Although only the external shape was represented by the model, mass distribution was assumed accurate. In this report the modeling of the water was the most complex area however the SPH method was considered superior to the FE method due to it’s ability to run over several hundreds of milliseconds with no numerical instabilities. The report was intended to be of use for improving the safety of Helicopter flotation devices. Simulation of the water impact in FEA was carried out due to the costs of attempting full-scale experimental impact testing of the actual system.

Marco Anghileri[1] also evaluated the SPH method, stating that the Lagrangian FEA technique results in distortion of the elements when modeling a fluid structure. The absence of meshing in the SPH model is considered to be advantageous in fluid modeling as it avoids such distortion. Although the SPH method also follows a Lagrangian basis it represent mass as particles where the coordinates follow the fluid movement. Such techniques allow mass conservation which does not require the level of computation of traditional FEA techniques. Anghileri’s findings did not fully support the popularity of the use of the SPH method, allowing that qualitatively it may have supported the empirical data, however the model used to characterize the water was considered to have negatively impacted the numerical results. He also noted that an extremely large number of points were required for the model to produce results that remotely agreed with the empirical data.

2.3.3 UAV Impact

The issue of whether a UAV is able to withstand the stresses on impact has very little research surrounding it. The majority of hydrodynamic impact research conducted has concerned such vehicles as ships and helicopters. In the case of helicopters the analysis has been primarily theoretical due to the size, weight and expense of the helicopters meaning
that practical testing would be costly and difficult. Practical testing of a small UAV, how-
ever, would be far less difficult as the smaller size makes it possible to carry out such tests
in an ordinary sized pool and any damage to the aircraft would incur far less expense than
that for a helicopter or full sized airplane. Gregory A. Zink[28, 30] provided both a paper
and a thesis on the topic of simulating the impact of a UAV with water. The focus was on
the Cormorant UAV design, proposed by Lockheed Martin, which was to be launched and
recovered from a submerged nuclear submarine. Zink conducted a Computational Fluid
Dynamics (CFD) simulation utilizing code, which modeled both “compressible”, and “in-
compressible” ensemble averaged Navier-Stokes equations. The CFD analysis was carried
out for several different drop heights, which each yielded different results. Fig 2.3 shows
the data obtained for the different drop heights. The data was shifted so that impact for
each of the drop heights was at zero seconds.

The results from the CFD analysis were then used to perform an FEA study in Ansys to
analyze the structural effects. As the Cormorant was designed to be fully submerged after
impact the simulations took into account the effect of the pressures experienced during the
submersion. It is while under these pressures that the models predicted a failure of the inlet
close-off door as the water free-surfaces close around the inlet causing trapped air which
becomes further compressed as the UAV submerges deeper.
2.4 Summary

Although a reasonable amount of research has been done into water-entry, it is primarily theoretical and very little has been done to assess the feasibility of UAVs that would be recoverable from water. In particular no experimental data has been presented for the impact loads experienced in the case of a UAV crash landing at sea. This is an important issue as UAVs become more and more widely used for surveillance projects such as observing wildlife in coastal areas. Actual physical impact tests with water have been avoided when analyzing full scale aircraft and helicopters due to the costs involved in such ventures and therefore when simulating the impact it was necessary to develop models of the water which provided various difficulties and inaccuracies.

2.5 Hypothesis

The two primary aspects of analysis in this report are the practical testing and the FEA analysis. The practical testing is intended to collect data on the behavior of the UAV during impact with water. To be specific, the accelerations at points along the wing spars which create stresses within the airframe and the time-transient pitch and roll angles corresponding to these loads. It is expected that the oscillations in pitch and roll angle data will correlate to the accelerometer data.

The Ansys FEA analysis of the loading due to acceleration was applied to just the wing spars to evaluate the feasibility of using the wing spars to attach the wings to the waterproof central fuselage. It is predicted that some modifications in design may be necessary to account for the increased stresses experienced by the wing spars due to the loading no longer being primarily distributed across the EPP foam.
Chapter 3

Methodology

3.1 Impact Testing

3.1.1 Initial Concept

In order to create an accurate model of the stresses imposed on the airframe under impact with water it is necessary to collect actual data from impact testing which represents the forces experienced during flight and impact. From past test flights data was gathered on the typical flight speeds and landing velocities of the Zephyr when flown over land. Using this information a testing platform for water impact could then be developed.

The initial idea for performing hydrodynamic impact analysis was to develop a testing rig based on those in operation at Langley research center. The concept involves swinging the airframe from a known height so that it would impact with the ground at specified landing angles and velocities. The Langley Rigs are currently used to test full sized aircraft under impact with concrete
CHAPTER 3. METHODOLOGY

Figure 3.1: NASA Helicopter Swing Test at Langley Research Center

Based on data collected during previous flight tests a typical RitewingRC Zephyr UAV will fly at a velocity of 34mph and land on ground at a velocity of 17mph at an angle of 0 degrees. To allow for the various conditions that the UAV might operate in, the testing rig was to be set up such that the airframe would be tested from landing angles of 10 degrees and velocities of 20mph so that the maximum stresses likely to be experienced by the airframe during impact could be accounted for. In order to set up the testing rig for these landing conditions the equations for a simple pendulum were utilized to work out initial conditions required to produce the required landing angle and velocity.

\[ v = \sqrt{2gL(1 - \cos(\theta_{\text{max}}))} \]  \hspace{1cm} (3.1)

\[ h = L - L\cos(-\theta_{\text{max}}) \]  \hspace{1cm} (3.2)
Where \( v \) is the velocity at the bottom of the swing, \( L \) is the length of the wire, \( \theta_{max} \) is the angle with the vertical that the pendulum is released from and \( h \) is the height it is released from (See fig 3.2).

\[
\theta_{max} = \arccos\left(-\frac{8.94^2}{20g}\right) = 114.03^\circ
\] (3.3)

\[
h = 10 - 10\cos(-114.03) = 14.07 \text{m}
\] (3.4)

In order to achieve the velocities expected, the set-up would require a ladder that was approximately 15 meters high, for a pendulum test with a 10 meter long wire, to release the UAV from and two more ladders at 10 meters to create the rig for the pendulum.
3.1.2 Revised Concept

Release heights of 15 meters would be difficult to achieve as stand alone ladders of that height are not readily available. Such large heights would also allow for a large margin of error in the velocity data due to discrepancies in release height measurements and the effects of wind on the swing. A launcher concept was instead devised in which a launcher, designed by the Embry-Riddle team participating in the Student Unmanned Aerial Systems Competition, was used to send the Zephyr into the water without any on board power supply. This launcher is made up of PVC tubing and relies on a Dewalt power drill to pull the shuttle up the ramp and propel the airframe (shown in fig3.3). The drill is directly connected to a 24 volt power supply.

![New Launch Concept](image)

**Figure 3.3: New Launch Concept**

The testing rig would also incorporate a grid at water level and a high speed camera focused on the grid to provide extra information on the exact landing conditions which may be calculated from the position at each time frame (see fig 3.4).
3.1.2.1 Accelerometers for Data Collection

Before setting up the testing rig the Zephyr was equipped with five accelerometers. One at the ends of each wing, one in the center of the fuselage and two on either side of the center fuselage. All of the accelerometers were positioned adjacent to the wing spars (see fig 3.5). These accelerometers were then wired up to a central located Arduino which was programmed to read each accelerometer and record the data to an SD card during flight. With the data gathered from the accelerometers at impact with water it would then be possible to observe the extent of the loading that the spars were subjected to upon impact.

The aircraft before weighting had a mass of 0.992 kg. It was weighted to approximately typical flight weight (2.15-2.6 kg) and balanced according to typical Center of Gravity (along the center line of the fuselage and 3 1/2 in forward of the motor mount).
Before impact testing it was essential to ensure that the accelerometers were reading the data correctly and alter the code to account for any inaccuracies. To do so several tests were carried out in the laboratory to read the data provided when the UAV was motionless and when it was being dropped directly onto a table. This allowed comparison of the data retrieved with the expected data from such conditions for X, Y and Z acceleration.

This brief testing yielded the following results:
For the stationary UAV

<table>
<thead>
<tr>
<th></th>
<th>X-Acceleration (g)</th>
<th>Y-Acceleration (g)</th>
<th>Z-Acceleration (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acc 1</td>
<td>0.1</td>
<td>-0.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Acc 2</td>
<td>0.2</td>
<td>0.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Acc 3</td>
<td>0.1</td>
<td>-0.0</td>
<td>-1.0</td>
</tr>
<tr>
<td>Acc 4</td>
<td>0.3</td>
<td>0.0</td>
<td>-1.0</td>
</tr>
<tr>
<td>Acc 5</td>
<td>0.2</td>
<td>0.1</td>
<td>-0.9</td>
</tr>
</tbody>
</table>

Table 3.1: X,Y, Z Accelerations when Stationary

For the table drop test

<table>
<thead>
<tr>
<th></th>
<th>X-Acceleration (g)</th>
<th>Y-Acceleration (g)</th>
<th>Z-Acceleration (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Before Impact</td>
<td></td>
</tr>
<tr>
<td>Acc 1</td>
<td>0.29</td>
<td>-0.28</td>
<td>1.28</td>
</tr>
<tr>
<td>Acc 2</td>
<td>0.32</td>
<td>0.16</td>
<td>1.51</td>
</tr>
<tr>
<td>Acc 3</td>
<td>0.6</td>
<td>-0.4</td>
<td>-3.14</td>
</tr>
<tr>
<td>Acc 5</td>
<td>0.76</td>
<td>0.59</td>
<td>-1.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>At Impact</td>
<td></td>
</tr>
<tr>
<td>Acc 1</td>
<td>1.28</td>
<td>-2.12</td>
<td>8.21</td>
</tr>
<tr>
<td>Acc 2</td>
<td>0.16</td>
<td>-2.36</td>
<td>13.12</td>
</tr>
<tr>
<td>Acc 3</td>
<td>3.59</td>
<td>-7.62</td>
<td>-13.22</td>
</tr>
<tr>
<td>Acc 5</td>
<td>-2.06</td>
<td>1.63</td>
<td>6.9</td>
</tr>
</tbody>
</table>

Table 3.2: X,Y, Z Accelerations on Impact with Table

The table shows acceleration in all three axes directly before and during impact with the table. The Zephyr was dropped from a height of 0.5 meters above the table and landed at a slight pitch down angle.

\[ v = \sqrt{2g \times 0.5} = 3.132 \text{m/s} \quad (3.5) \]

Momentum:

\[ p = mv = 0.869 \times 3.132 = 3.107 \text{kgm/s} \quad (3.6) \]

assuming force is constant and time to decelerate to be approximately 0.1-0.2 seconds (fig3.6).
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\[ F = \frac{3.107}{0.1} = 31.07 = 3.17g \]  

(3.7)

\[ F = \frac{3.107}{0.2} = 15.54 = 1.58g \]  

(3.8)

In comparison with the actual results the accelerations experienced seemed to be higher than these values on impact however some post-processing of the data would still be necessary to ensure accurate data readings and account for the difference in reference frames for each accelerometer. In order to do this accelerometer readings were taken for a time period during which the aircraft was on the ground, stationary, as well as for when it was moved to a 90 degree pitch angle and a 90 degree roll angle. When at stationary the accelerometers should have all had a reading of 1g in the z direction and 0g in both the x and y direction due to the only force acting on the airframe being a result of gravity. It is possible to then rotate the data collected during this stationary period using a rotation matrix and achieve as close to these values as possible. These matrices may then be applied to the data obtained from the physical impact testing.

Using the reference frame as shown in fig 3.5 the rotation matrices for yaw pitch and roll are
CHAPTER 3. METHODOLOGY

\[ R_{\text{roll}}(\alpha) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha) & -\sin(\alpha) \\ 0 & \sin(\alpha) & \cos(\alpha) \end{bmatrix} \] (3.9)

\[ R_{\text{pitch}}(\beta) = \begin{bmatrix} \cos(\beta) & 0 & \sin(\beta) \\ 0 & 1 & 0 \\ -\sin(\beta) & 0 & \cos(\beta) \end{bmatrix} \] (3.10)

\[ R_{\text{yaw}}(\gamma) = \begin{bmatrix} \cos(\gamma) & -\sin(\gamma) & 0 \\ \sin(\gamma) & \cos(\gamma) & 0 \\ 0 & 0 & 1 \end{bmatrix} \] (3.11)

Multiplying these together gives

\[ R(\alpha, \beta, \gamma) = \begin{bmatrix} c(\beta)c(\gamma) & c(\gamma)s(\alpha)s(\beta) - c(\alpha)s(\gamma) & c(\alpha)c(\gamma)s(\beta) + s(\alpha)s(\gamma) \\ c(\beta)s(\gamma) & c(\alpha)c(\gamma) + s(\alpha)s(\beta)s(\gamma) & -c(\gamma)s(\alpha) + c(\alpha)s(\beta)s(\gamma) \\ -s(\beta) & c(\beta)s(\alpha) & c(\alpha)c(\beta) \end{bmatrix} \] (3.12)

First finding the yaw, pitch and roll of each accelerometer when the Zephyr is stationary and then inputting those values into the above matrix will produce the rotation matrix. This matrix may then be multiplied by the x,y and z acceleration values to rotate them to the body reference frame of the aircraft. This was all done in MATLAB (see Appendix 1). The fsolve function allowed the values of yaw, pitch and roll to be found for each accelerometer to give an output of as close to 0g,0g,1g for stationary x,y and z values as possible. The result of this are shown in table 3.3.
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<table>
<thead>
<tr>
<th></th>
<th>Pitch Angle (deg)</th>
<th>Roll Angle (deg)</th>
<th>Yaw Angle (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerometer 1</td>
<td>-5.6</td>
<td>-6.3</td>
<td>2.1</td>
</tr>
<tr>
<td>Accelerometer 2</td>
<td>-0.5</td>
<td>-6.0</td>
<td>23.0</td>
</tr>
<tr>
<td>Accelerometer 3</td>
<td>-1.1</td>
<td>-174.3</td>
<td>-169.2</td>
</tr>
<tr>
<td>Accelerometer 4</td>
<td>6.5</td>
<td>-170.3</td>
<td>4.6</td>
</tr>
<tr>
<td>Accelerometer 5</td>
<td>10.0</td>
<td>-169.9</td>
<td>-174.3</td>
</tr>
</tbody>
</table>

Table 3.3: Pitch, Roll and Yaw Angles for Rotation Matrix

To check the validity of this solution the rotation matrices were then applied to the data for the 90 degree roll test and the 90 degree pitch test and then the stationary pitch and roll found for the rotated data from eqs 3.13-3.14 were subtracted from the pitch and roll for the rotated 90 degree data and and the resulting pitch and roll values were compared to the expected values.

\[
Pitch = \arctan\left(\frac{y}{\sqrt{x^2 + z^2}}\right) \quad (3.13)
\]

\[
Roll = \arctan\left(\frac{x}{\sqrt{y^2 + z^2}}\right) \quad (3.14)
\]

The pitch values for the 90 degree pitch rotation are shown in fig 3.7.

![90 degree pitch rotation](image)

Figure 3.7: Pitch Angle Variation for 90 Degree Rotation
The graph shows the maximum angles to be at approximately 90 degrees when rotated and 0 when stationary on the ground, validating the application of the rotation matrix.

### 3.1.2.2 Testing of Launcher Concept

Validation of the launcher concept was initially carried out with an older airframe during which videos of the launcher were taken. Photos were taken of the landing using a high speed camera so that crude angles and velocities could be gathered.

The Launcher was propped up at different angles to achieve different impact angles and four launches were done for each angle. Approximate landing angles were obtained from images taken with the high speed camera by a small program called ScreenScales. The landing angles obtained were fairly consistent for each launch position. For the three launch positions the impact angles were approximately 25 degrees, 20 degrees and 11 degrees. This was considered to be a true representation of impact when at sea due to turbulence in the water.

![Figure 3.8: Pre-Test Impact Angle](image)

The approximate velocities of impact were found to be less than that of the typical landing velocities, averaging at 13.83 mph. This was rectified in the actual testing by supplying more power to the launcher. It was also considered that the wind speed and
direction may have adversely affected the results. Videos taken of the launch allowed for comparison of the Zephyr’s velocity at launch and at impact.

Results taken from one launch had a velocity of 14.59mph which produced an impact velocity of 13.88mph. After the power was increased impact velocities of 23.54mph were achieved.

3.1.2.3 Final Test Plan

For the actual testing the Zephyr was initially weighed so that its dry weight could be documented for comparison with its end weight to see if there was a significant water retention and if that could have an effect on the results. The dry weight was intended to be typical flight weight when in service and was therefore weighted appropriately. The high speed camera and tripod were then set up directly facing the expected landing position for the airframe with the grid positioned on the other side. The launcher was set up adjacent to the pool aiming towards the line of sight of the camera with the Zephyr positioned on it. Before launching, the wind speed was recorded using an anemometer so that it could be taken into consideration with the results if there was a strong headwind or tailwind. The important data to gather in order to analyze the stresses experienced on the structure were the decelerations at each wing and in the center section after impact. These decelerations could be recorded during flight from the LIS331 3-axis accelerometers positioned on the airframe. Before each run the SD card was cleared and then data-logging would be started at the beginning of the run. For recording the impact velocity and angle the grid of known square dimensions and high speed camera data were used. It was therefore also necessary to begin camera recording at the beginning of each run. After initiation of the data-log and recording equipment, the Zephyr would be launched. Upon retrieval, data-logging and recording were stopped. The Zephyr was then reweighed for its wet weight and the process was repeated a total of four times for each launch angle (See Results chapter for the collected data).

Based on the equations given by Von Karmen[16], predictions may be made for the impact force experienced were the Zephyr to land at a zero angle. These predictions could then be compared with the results obtained. Assuming a zero degree landing angle the under surface could be described as a wedge bottomed surface with a 15 degree angle. The
equation for the impact force was taken from equation 2.5. For water \( \rho = 1000 \text{kg/m}^2 \), \( x \) is related to the width of the under-surface of the center-section and is \( 0.154/2 \) (m) and \( \alpha \) is the angle of inclination of that surface to the water which is approximately 15 degrees. Therefore, for a typical landing velocity of \( 8.94 \text{m/s} \):

\[
P = \frac{v_0^2 \cot \alpha \rho \pi x}{(1 + \frac{\pi x^2}{2W})^3} = \frac{8.94^2 \times \cot 15}{(1 + \frac{1000 \times 9.81 \times \pi \times 0.0752^2}{2 \times 0.99})^3} \times 1000 \times \pi \times 0.0752 = 2.65 \text{N} \quad (3.15)
\]

This would be for a smooth landing with a zero degree landing angle.

### 3.2 FEA

Once the values for the material properties and the loads experienced on impact with water had been gathered it would then be possible to input this information into Ansys Workbench so that different designs may be considered and simulated for the conditions likely to be experienced. As the primary areas of concern were the wing spars, a basic model of the spars was developed for analysis in Ansys. The basic wing spar geometry was modeled in solidworks using solid elements to create hollow carbon fiber tubes for the center spars and solid fiberglass rods for the wing spars (see fig 3.9 for spar positions). Material properties were not provided and had to be taken from online data sheets based on the properties known (see table 3.4). The airframe was assumed to be symmetrical in dimensions and properties. This meant that it was possible to only model the spars for one half of the airframe. The model was then exported to Workbench for meshing and application of the loads. The mesh used was a 1mm quad mesh for the whole model. The accelerations were applied to the spars as point loads in all three axes based on the equation \( F = ma \) (see figure 3.10). The point A was set as a fixed stationary point in the model. To account for the acceleration for that point the values were subtracted from the accelerations for the point loads applied to the points shown in figure 3.10. The masses were defined for each point as the mass of the section of the aircraft that was assumed to be associated with the loading for that point. Validation would then allow for loads on improved models to be tested for using ANSYS simulations on imported CAD models of future designs.
**Figure 3.9: Wing Spar Locations**

<table>
<thead>
<tr>
<th>Component Type</th>
<th>Center Spars</th>
<th>Wing Spars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transverse Young’s Modulus (E)</td>
<td>3.45 GPa</td>
<td>12.411 GPa</td>
</tr>
<tr>
<td>Longitudinal Young’s Modulus (E)</td>
<td>228 GPa</td>
<td>17.23 GPa</td>
</tr>
<tr>
<td>Transverse Poisson’s Ratio (ν)</td>
<td>0.34</td>
<td>0.3</td>
</tr>
<tr>
<td>Longitudinal Poisson’s Ratio (ν)</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Transverse Shear Modulus (G)</td>
<td>1.287 GPa</td>
<td>5.52 GPa</td>
</tr>
<tr>
<td>Longitudinal Shear Modulus (G)</td>
<td>20 GPa</td>
<td>5.52 GPa</td>
</tr>
<tr>
<td>Yield Strength</td>
<td>3.7 GPa</td>
<td>0.414 GPa</td>
</tr>
<tr>
<td>Inner Diameter</td>
<td>3.5mm</td>
<td>0</td>
</tr>
<tr>
<td>Outer Diameter</td>
<td>5.3mm</td>
<td>2mm</td>
</tr>
</tbody>
</table>

Table 3.4: Material Properties of Wing Spars[2, 12]
Figure 3.10: Load Application to Spar Model
Chapter 4

Results

4.1 Descriptive Statistics

4.1.1 Effect of Angle

Testing provided a clear picture of the loading experienced by the aircraft on impact with water. Various issues were encountered with working out the angle of impact as the aircraft typically landed on its left wing as opposed to a straight landing, which created difficulties in obtaining impact angles from photographs taken. The grid provided little assistance to finding the impact speed and angle as the squares were too small and the high speed setting on the camera sacrificed resolution.
CHAPTER 4. RESULTS

Figure 4.1: Typical Landing on Left Wing.

It was considered possible that the airframe was built asymmetrical to account for torque of the engine in flight and as the testing involved no power being supplied during flight there was no torque to counteract the balance of the aircraft. CAD files supplied for the aircraft were analyzed for this possibility but did not show asymmetry (see fig 4.2 and 4.3).

Figure 4.2: Left Wing Dimensions (mm)
Other possible factors that would have caused such landings are wind direction or potential errors in balancing to center of gravity or positioning control surfaces. Off center landings can be considered an inevitability in off-shore operations.

Unfortunately finding impact angle from trigonometrical analysis of accelerometer data also proved unsuccessful as it would have been necessary to only take data points immediately before impact and the data proved too noisy at any one point in time for accurate measurements. Analyzing the results with launch angle comparisons, however, showed little variation between impact loading with regards to angle. The aircraft was launched at two different angles. Unfortunately, during testing, the threaded rod attached to the power drill sheared, rendering the launcher unusable. This resulted in fewer variables being tested for.

When analyzing the data obtained from the testing it was necessary to omit the data given by accelerometer 4 as the values it was producing, in particular for the x-axis, were observed to be inaccurate. Figure 4.4 shows that the accelerometer 4 values, even after applying the rotation matrix, do not correlate well with the data provided by the other accelerometers. It is believed that this was due either to the accelerometer being faulty or errors in data being caused by some damage occurring during the mounting of the accelerometer in the wingtip.
CHAPTER 4. RESULTS

4.1.2 Accelerometer Data

The data provided by the accelerometers was imported into excel spreadsheets and graphed for all three axes. The results for test 1 are compared with tests 6 and 7 for their different landing styles. See Appendix 2 for results from the other tests.

4.1.2.1 Maximum Accelerations

Maximum acceleration/ deceleration values for each axis was found from the data and is shown in table 4.2.

<table>
<thead>
<tr>
<th></th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
<th>Test 6</th>
<th>Test 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max X-Acceleration (g)</td>
<td>10.1</td>
<td>5.8</td>
<td>3.7</td>
<td>7.9</td>
<td>2.4</td>
<td>28.0</td>
<td>2.12</td>
</tr>
<tr>
<td>Max Y-Acceleration (g)</td>
<td>13.5</td>
<td>5.6</td>
<td>8.7</td>
<td>7.1</td>
<td>7.3</td>
<td>24.4</td>
<td>3.74</td>
</tr>
<tr>
<td>Max Z-Acceleration (g)</td>
<td>25.0</td>
<td>23.7</td>
<td>6.1</td>
<td>23.9</td>
<td>5.3</td>
<td>24.4</td>
<td>9.20</td>
</tr>
<tr>
<td>Launch Angle (deg)</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 4.1: Maximum X, Y and Z Accelerations

4.1.2.2 Test 1

The first run yielded the highest maximum z-acceleration as well as high x and y accelerations. Images of the impact show a nose landing, slightly angled toward the left wing.

The graphs show initial impact caused a deceleration of almost 15g at the nose in the y-direction. The nose then became submerged as the wingtip continued to move forward,
causing a moment around the nose. This resulted in a 10g peak in x-acceleration. The acceleration in all three axes was then momentarily zero before the buoyancy of the aircraft caused it to exit the water and land a second time. This resulted in a small second period of increased acceleration, approximately 0.5 seconds after the first period of acceleration had subsided.
Figure 4.5: Test 1 Still Frames
4.1.2.3 Test 6

The sixth run yielded a similar maximum z-acceleration to the first run but highest accelerations in both the x and y-axes. During this run, the aircraft landed at a steep roll angle (see Figure 4.6: Test 1 Acceleration Charts).
fig 4.9). Initial impact resulted in accelerations of no more than 5g in each axis. However, approximately half a second after initial impact, high accelerations of up to 28g occurred in all three axes. These peaks correspond to fourth still in figure 4.9. In this frame the left wing has become submerged as the right wing continues to move forward. This caused peaks of 24.4g and 28g in the y-axis and x-axis respectively, due to the moment created in the right wing.

The submerged left wing now acts around a center of buoyancy, around which the moment gave rise to a maximum acceleration of 24.4g at accelerometer 3 (the most submerged point on the wing).
4.1.2.4 Test 7

For the seventh run the aircraft landed on its left wing, similarly to the sixth run. In this case, however, a more shallow roll angle was achieved, resulting in a smoother landing (see fig
4.10). Consequently the maximum accelerations for this landing were considerably lower, in all three axes, than for the first and sixth runs. A comparison with accelerations from the sixth run show x and y values to be more than 20g lower and the z acceleration to be more than 15g lower for this run. This would imply that the lesser roll angle had a significant effect on the accelerations experienced.
Figure 4.9: Test 7 Still Frames
Figure 4.10: Test 7 Acceleration Charts
4.1.2.5 Effect of Launch Angle

For the two launch angles it was noted that the maximum impact accelerations were very close. The three runs with the highest acceleration data did not all occur at the highest launch angle (as shown in table 4.1).

<table>
<thead>
<tr>
<th>Run no.</th>
<th>Launch Angle(deg)</th>
<th>Max Acceleration (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>25.074</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>23.939</td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>28.030</td>
</tr>
</tbody>
</table>

Table 4.2: Angle-Acceleration Comparison

Analysis during pre-testing estimated the landing angles at the 5 degree and 10 degree launch angles to be approximately 11 degrees and 20 degrees respectively. This would indicate that landing angles may not have as great of an effect on loading as previously expected.

4.1.2.6 Comparison with Previous Literature

Comparison of the results obtained through these tests with the data from Zink’s[30] research showed maximum accelerations to be higher in the case of the Zephyr for similar impact velocities. Impact velocity obtained for test 1 through frame by frame pixel analysis of the videos taken with the high speed camera were 23.54 mph. Zink’s 25 ft drop (as shown in figure 2.3), which produced an impact velocity of approximately 27 mph resulted in a maximum acceleration value of 9.47 gs. It is important to note that the design on the cormorant is such that it is intended to fully submerge upon impact, which results in the deceleration to zero velocity occurring over a longer time period (2 seconds as opposed to 0.5 seconds for the Zephyr in test 1). The higher acceleration values would therefore be expected for the Zephyr.

4.1.3 ANSYS

For the FEA analysis both von-Mises Stresses and deflections were plotted. The von-Mises stresses were highlighted as they are typically used to predict yielding of a material. The
maximum stresses are experienced in the center of the hollow carbon fiber tubes. In this occurrence, the yield strength of both materials (table 3.4) is greater than the maximum value for the von-Mises stress. Thus, failure is not predicted.

The Maximum deflections are observed to assess the structural support offered by the current wing spars. These deformations are predicted to be up to 10mm in the thin fiberglass spars, which is comparable with the images taken during testing.

The loads, applied to the model, that yielded these results were a maximum of 7.34 N. In comparison with the calculations in the methodology this appears to be a reasonable value, considering the value of 2.65N (from Von-Karmen’s equations) was for a landing of zero impact angle. Although no failure has occurred it can be observed that the fiberglass spars offer little structural support and the high stresses in the center may cause failure after repeated impacts within the carbon fiber spars.

![Von Mises Stresses](image)

Figure 4.11: Von Mises Stresses
Figure 4.12: Deformation of Wing Spars
Chapter 5

Discussion, Conclusions, and Recommendations

5.1 Discussion

The design of a UAV capable of landing at sea is one that would have many useful applications. The Zephyr Airframe used in this testing proved to handle water landing well as the EPP foam proved to be both buoyant and waterproof. The loads experienced during impact however caused flexing in the wings that would, although not having caused failure in the wing spars in the Ansys model, create high stresses and therefore require a different type of wing spar to attach the wings securely to the center-section in the proposed model. A design in which the thin fiberglass wing spars were perhaps replaced with a more rigid spar that could offer more structural support would most likely be sufficient. The Ansys model would allow for various wing spar set-ups to be tested before implementation.

It was interesting to note that the surface of the aircraft that was the point of initial contact with the water had a significant effect on the types of loading and flexing experienced. The high roll angle of test 6 produced the highest overall accelerations, whereas the high pitch angle of test 1 also produced significant accelerations, particularly in the z-axis. This would indicate that impact angle has a significant effect on the loading experienced. Maximum accelerations of above 20g, in all three axes, for test 6 suggests that impacting
the water at a high roll angle would be the least desirable scenario. However as turbulence at sea is unpredictable, this scenario may not always be avoided.

Overall the Zephyr provided a successful platform for the development of a water-worthy UAV. It is lightweight and is therefore easy to transport and recover from the water. Weighing before and after being in the water showed little water retention and the flexibility of the structure would be advantageous if the UAV were to land at an unexpected angle as it would provide damping of the loads experienced. The main issue in making the design fully viable in a primarily ocean based application is the waterproofing of the avionics which would be solved by a waterproof encapsulating center-section.

5.2 Conclusions

- A high roll angle tended to correlate to the highest overall accelerations in all three axes.
- There was also a correlation between high pitch angles and high accelerations, although primarily in the z axis.
- The launch angle had little to no effect on the accelerations at impact.
- Accelerations experienced in testing for a water-landing UAV were higher than the accelerations from previous literature for a submerging UAV.
- FEA results indicate that there may be a considerable amount of flexing in the wings during impact.
- Test results in some cases matched the analytical results from Von-Karmen’s equations.

5.3 Recommendations

Were more time and resources available it would have been useful to have incorporated gyroscopes into the testing to provide clearer data on the pitch and roll angles as this was
difficult to accomplish with purely acceleration data. Replacement of accelerometer 4 as well as positioning one more accelerometer half way across the length of each wing would also provide a better overall picture of the impact over the entire airframe.

The most unfortunate issue encountered during testing was that on the day that testing occurred there were some technical issues which caused the launcher to break, cutting short the number of tests performed. Originally it was intended that tests would be done for 3 different launch angles at 2 different launch velocities. With more time the information provided from a greater number of tests could have helped considerably in drawing more accurate conclusions on the hydrodynamic impact of a UAV.

Materials testing would have also been useful, particularly for inputting the material properties into the Ansys model, as information on the materials was limited and was primarily gathered from online data sheets.
Appendix A

First Appendix

A.1 Section 1

A.1.1 MATLAB fsolve function

Function

function F1 = YPR_solve_1(x,raw1)
    yaw1=x(3)*(pi/180);
    roll1=x(2)*(pi/180);
    pitch1=x(1)*(pi/180);
    Y1 = [cos(yaw1),-sin(yaw1),0; sin(yaw1),cos(yaw1),0;0,0,1];
    R1 = [cos(roll1),0,sin(roll1); 0,1,0; -sin(roll1),0,cos(roll1)];
    P1 = [1,0,0;0,cos(pitch1),-sin(pitch1); 0,sin(pitch1),cos(pitch1)];
    F1=(P1*R1*Y1*raw1)-[0;0;sqrt(raw1(1)^2+raw1(2)^2+raw1(3)^2)]

Solving

clc clear x0=[0;0;0];
    raw1 = [xacc; yacc; zacc]; %Input raw acc data here
[x,fval]=fsolve(@YPR_solve_1,x0,[],raw1)
Rotation Matrix

cle

clear
pitch=pitch1*(pi/180); % from fsolve
roll=roll1*(pi/180); % from fsolve
yaw=yaw1*(pi/180); % from fsolve
Y = [cos(yaw),-sin(yaw),0; sin(yaw),cos(yaw),0;0,0,1];
R = [cos(pitch),0,sin(pitch); 0,1,0; -sin(pitch),0,cos(pitch)];
P = [1,0,0;0,cos(roll),-sin(roll); 0,sin(roll),cos(roll)];
rot=P*R*Y;
Appendix B

Second Appendix

B.1 Section 1

Still frames for the remaining tests. The landing was out of the frame for test 4.
Figure B.1: Still Frames for Test 2
Figure B.2: Still Frames for Test 3
Figure B.3: Still Frames for Test 5
Appendix C

Third Appendix

C.1 Section 1
Figure C.1: X, Y, Z Accelerations for Test 2
Figure C.2: X, Y, Z Accelerations for Test 3
Figure C.3: X,Y,Z Accelerations for Test 4
Figure C.4: X,Y,Z Accelerations for Test 5
Bibliography


