Analysis of Rocket Assisted Ground Take off of the Yves Rossy Wingsuit

A project present to
The Faculty of the Department of Aerospace Engineering
San Jose State University

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Master of Science in Aerospace Engineering

By

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approved by

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Faculty Advisor

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UNIVERSITY

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Spring 2015

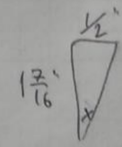
Contents

old design — New

me { Bottom delt to knee ish $26\frac{1}{2}$" — 35"

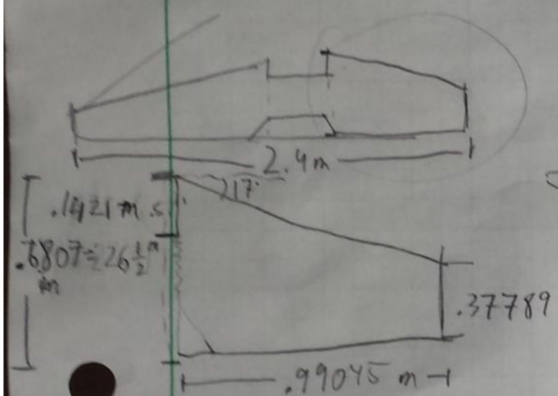
Chest (no shoulders) width: $16\frac{1}{2} = 41.91$ cm

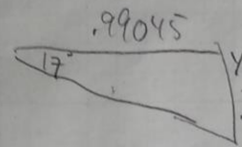
Proportion: .384 26.7



$\tan = \frac{.5}{1.4375}$ $x = 19.179°$

17°





$\tan 17° = \frac{Y}{.99045}$ $Y = .3028$

area $= \frac{.6807 + .37789}{2} \times .99045 = .5242\ m^2$

$.5242 \cdot 2 = 1.0485$ of wings m^2

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$.5386 \times .4191 = .2257 m^2$

$C_L = \frac{L}{\frac{1}{2}\rho V^2 S} = \frac{281\ lbs}{\frac{1}{2}\ .5258 \frac{kg}{m^3} \times 124.274 mph^2 \cdot 1.2742 m^2}$

$= \frac{1249.95\ N}{\frac{1}{2} \cdot .5258 \cdot 55.56^2 \cdot 1.2742} = 1.208 = C_L$

$C_D = \underline{208} \cdot \underline{925.23} = .895 = C_D$

$AR = \frac{2.4^2}{1.2742} = 4.52$

$\tan\theta = \frac{1}{281/208}$ $\theta = 53.49°$

$V_\infty = \sqrt{\frac{2\cos\theta}{.5258 \cdot 1.208} \cdot \frac{1249.95 N}{1.2742}}$

42.869 m/sec

95.895 mph

V_∞

Definition of terms

α =	angle of attack
AR =	Aspect Ratio
L =	Lift Force
D =	Drag force
C_l =	Coefficient of lift for an airfoil
C_L =	Coefficient of lift for a wing
C_d =	Coefficient of drag for an airfoil
C_D =	Coefficient of drag for a wing
W =	Weight of aircraft
Th =	Thrust
ρ_∞ =	Freestream density
V_∞ =	Freestream velocity
S =	Planform area
b =	chord length
s =	entropy

T =	Temperature
P_e =	Pressure at the exit nozzle
P_a =	Ambient Pressure
V_e =	Velocity of the propellant
$\dot{m}$ =	mass flow rate of propellant
A_e =	Area of the nozzle at the exit
lbs =	Pounds
N =	Newtons
S_{LO}=	Takeoff distance
μ_r=	Runway friction coefficient

1.0 Introduction

1.1 Motivation

The recreational use of flying has been done for several hundred years, since the days of helium and hot air powered balloons. Recreational flight has evolved: hang gliders, BASE jumping, and sail planes have come more into use, and have given people a greater feeling of personal flying. In 2007, Captain Yves Rossy successfully tested a jet pack that can fly using 4 kerosene fueled jet engines. The jet pack wing is in a delta configuration, with end plates on the wings. The jet pack can reach cruise speeds of 124 mph, and Rossy has flown across the English Channel, Mt Fuji, and over the city of Dubai. So far, it is the ultimate in recreational flying. However, Rossy's jet pack must jump out of an airplane or a helicopter to achieve the velocity to generate the lift necessary to begin and maintain flight.

1.2 Objective

It is hypothesized that this kind of jet pack can be modified to take off from a runway, while not sacrificing the feeling flying. This can be done by changing the aerodynamic design of the wing. However, this report will specifically focus on achieving ground take off by adding solid propellant rockets to assist in achieving take off from a runway. The following literature review demonstrates that this hypothesis is true.

1.3 Literature Review

1.3.1 Brief Relevant History

The earliest form of framed recreational flying could be traced back to 3rd and early 4th century in China, where the first manned hot air balloon is believed is believed to have occurred [2]. By the end of the sixth century in China, large kites had been made. As the kites became larger and larger, and more aerodynamically stable, people began to be placed in those kites, and the strings were eventually cut. This is the earliest form of hang gliding [1]. The next evolution of framed flight came in the form of gliders and sailplanes. Gliders and sailplanes are unpowered (i.e., no power plant) aircraft that usually have very long and narrow wings. This allows for lift to be achieved at low speeds, which is why some gliders and sailplanes achieve lift by being attached to an automobile by cable [4]. The SWIFT foot launched sail plane achieves lift by running down a hill, and hitting what are called "thermals" to perpetuate its flight [5]. The first glider to have some resemblance of flight came from Sir George Cayley in 1849 [6], and the Wright Brothers modified a glider for their first flight in 1903. Today, the usage of sailplanes and gliders is common in the world of recreational flying.

While those accomplishments were being made in framed flight, more personal forms of non-framed flight were being developed at the same time. The first milestone in non-framed flying would come from André-Jacques Garnerin, when on October 22, 1797; he successfully tested the first non-framed parachute [7]. The first intentional free fall jump was performed by Leslie Irvin in 1919 [8]. Since then, sky diving went from an activity exclusively performed by the military, to any civilian willing to jump out of a functional airplane.

Always looking for the next thrill, avid sky divers began to experiment and evolve the sport of skydiving. In 1978, the term BASE jumping was first coined. According to Berry, a sky diver jumps out of an airplane, or off a cliff, with a parachute and a body suit that has giant webbings between the arms and legs, and between both legs [10]. The BASE jumping suit looks like a flying squirrel. Capt. Rossy was both a fighter pilot and an avid sky diver/BASE jumper when he began to design his wingsuit. A more in depth discussion of Rossy's wingsuit will be performed in section 3.

1.3.2Rockets used for flight

Rocket assisted take off (RATO), which is sometimes referred to as Jet assisted take off (JATO), is the process where a rocket engine is attached to work in concert with a jet engine to assist in takeoff. It provides extra thrust to the aircraft to assist the aircraft in take-off when the jets can't generate enough thrust by themselves. Several experimental planes were made in this nature during World War II. Once in flight, the rocket engine would disengage, and the rest of the flight is conducted via the jet engines. As suggested by Jossie, large transport planes would need to incorporate a RATO system fueled by solid fueled rockets in order to shorten the takeoff distance and to take off from rough landing strips [9]. The rocket engine will employ ammonium perchlorate. Marcus Murbach, a propulsion specialist at NASA Ames, stated that ammonium perchlorate is the "secret sauce", as it is a powerful oxidizer that can help generate enough thrust for take-off.

Beyond WWII, RATO modifications were done to a C-130 Hercules for a mission known as Credible Sport. In 1980, when 52 American hostages were taken in Iran, the Department of Defense (DOD) ordered that a C-130 be modified to be able to take-off and land inside a 350 foot Iranian soccer stadium. Normally, a C-130 has a take-off distance of 1800 ft., and a landing distance of 1400 ft. [11]. As stated by Renner, these modifications came in the form of rockets: 30 rockets were attached to the newly anointed XFC-130H, with 8 rockets pointing forward for reverse thrust, 8 rockets pointing down for a soft landing, 8 rockets pointing back for increased thrust on take-off, and 2 rockets on each wing to correct for yaw, and 2 rockets on the tail [12]. The XFC-130H had several very successful test flights. However, the mission was ultimately aborted when the plane crashed due to the pilot engaging the landing rockets before touchdown. However, the rockets used for take-off never had a major issue, showing that rocket assisted take off can aid in ground take-off for Rossy's wingsuit.

2.0 Relevant Theory

2.1 Aerodynamics

Rossy's wingsuit has a cruise speed of 124 mph (55.56 m/s), and flies at an altitude between 6000 and 12500 feet. It is a completely subsonic flying vehicle; therefore the following theory applies to the wingsuit.

When an object is moving through air, it feels two different pressures: the static pressure, and the dynamic pressure. The static pressure is the pressure of the ambient air at a particular temperature, density, and altitude above sea level. The dynamic pressure correlates to the density of the freestream air, and the square of the velocity of the freestream air relative to the moving object. According Anderson, Equation 1 shows how to calculate the dynamic pressure [13]

$$_{\infty} = .5 \; _{\infty} \; _{\infty}{}^{2}$$

Equation 1

Anderson goes on to explain how the coefficients of lift and drag are found. Equation 2 and Equation 3 show the equation to find the coefficient of lift and drag for an airfoil, respectively [13].

Equation 2

$$= \frac{}{}$$

Equation 3

$$= \frac{}{}$$

Equation 4and Equation 5 are used to find the lift and drag for an entire wing, substituting the airfoil length b for the wing area S,

Equation 4

$$= \frac{}{}$$

Equation 5

$$= \frac{}{}$$

At steady, level flight, L=W and Th = D, with lift and drag always being perpendicular to each other. However, during maneuvers such as pitching, rolling, or yawing, lifting loads on the wings and the drag force vary, and can only be found experimentally. However, analyzing a plane under steady condition can is still an important method, which will be done in section 3.

The amount of lift an airfoil and wing can produce cannot be determined simply based on the geometry of the wing, airfoil, or aircraft. A wind tunnel must be used to gather such data. When a wind tunnel is used across a variety of airfoils and wings, the data does form a trend.

Figure 1 shows a typical α vs C_l for a subsonic wing [13]. The highest point on the line is called the maximum lift coefficient. When the graph ends, that is where the airfoil (or wing) stalls, and the lift becomes zero. The corresponding angle of attack is called the stalling angle. The point where the line crosses the angle of attack axis is called the zero lift angle of attack.

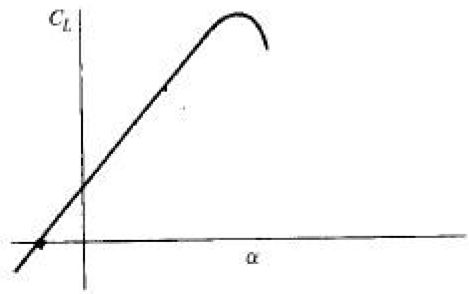

Figure 1. Typical coefficient of lift vs angle of attack [3]

Lift of a wing can be varied by any number of factors, such as length, configuration, area, chord length, camber, and several other factors. One major factor is the aspect ratio. The aspect ratio is the ratio of the square of the chord length (b) to the planform area (S). Or in other terms, AR = b^2/S. According to Raymer, the maximum coefficient of lift increases as the aspect ratio increases, as shown in Figure 2 [3]. The maximum lift coefficient also increases, and the amount of lift achieved at a given angle of attack is higher at a higher aspect ratio (for example: at $\alpha = 3^o$, a small aspect ratio wing could have a C_L = .1, while a large aspect ratio wing will have a C_L = .3). However, the stalling angle decreases as the aspect ratio increases.

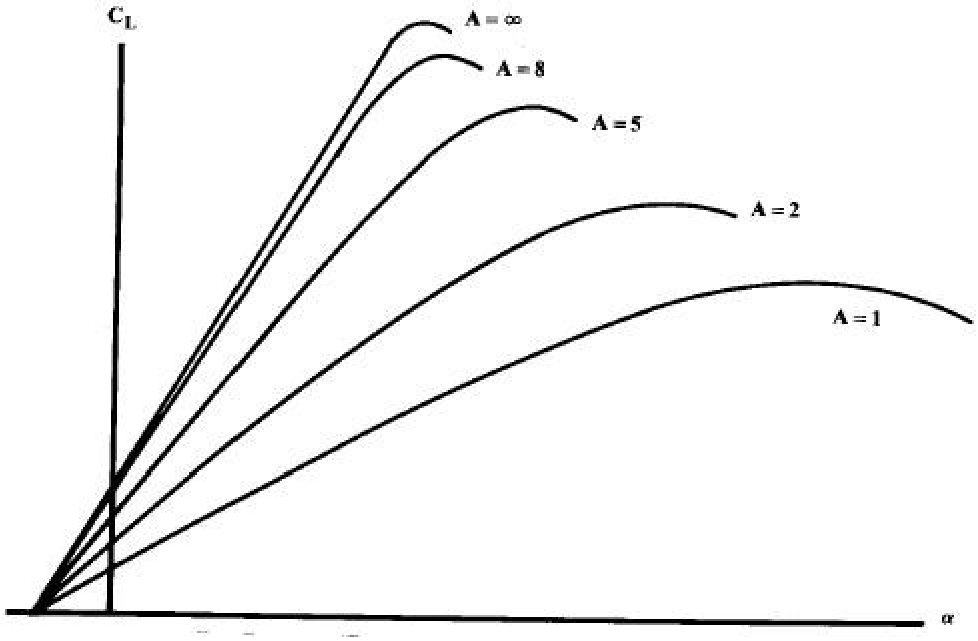

Figure 2. Effect of aspect ratio on lift

For a more extensive look at the aerodynamics of lift, and how design affects it, the reader is encouraged to read [3] and [13].

2.2 Propulsion

2.2.1 Turbojet

Rossy's wingsuit uses four P200-SX kerosene fueled turbojet engines, manufactured by Jet Cat. While the exact details of those jet engines are not available due to their proprietary nature, they are nonetheless turbojets, which will be looked at now.

According to Mattingly, Figure 3 shows an ideal turbojet, and its numbered stations [15]. A turbojet is made up several components: the compressor, the combustor, the turbine, and the nozzle. Each station corresponds to a location on the T-s diagram shown in Figure 4, and each number corresponds to a different station in the turbojet process [15]. Station zero is the freestream station: the air has not been altered at all; it has all of its freestream characteristics, such as pressure, temperature, density, etc. Station 2 corresponds to the air entering the compressor. Many of the qualities of the air from station 0 are the same as station 2, as can be seen in the corresponding numbers in Figure 4, as the total temperature at station 0 and 2 are the same. When the air has gone through the compressor and reaches station 3, it has been compressed isentropically, raising the pressure of the air and its total temperature. When it enters the combustor, the air is mixed with fuel and combustion takes place. At the end of the combustion phase, at station 4, the total temperature is at its highest in the cycle, and the amount of entropy generated has increased, as seen at station 4 in Figure 4.

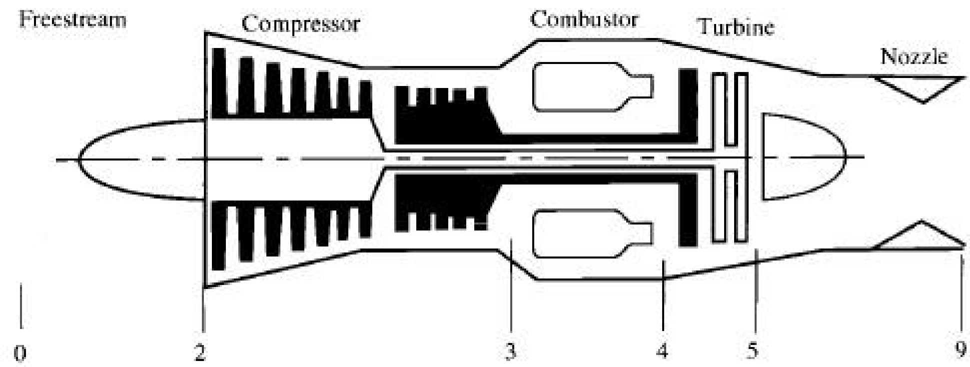

Figure 3. Station numbering for an ideal turbojet

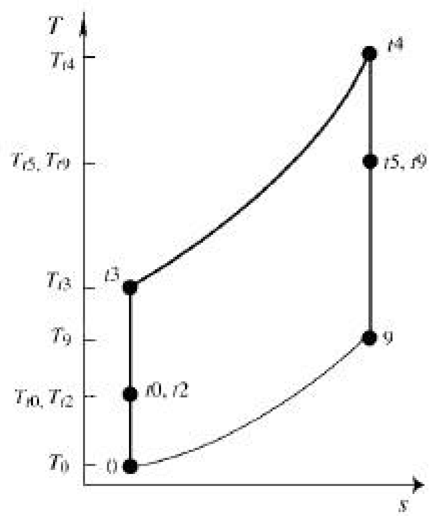

Figure 4. T-s diagram for an ideal turbojet

With the air at a very high temperature, it moves through a turbine, turning the turbine as it passes through it to station 5. At station 5, the total temperature drops, and the amount of entropy generated thus far remains unchanged. As the air exits the turbine, it begins to go through the nozzle, and then exits the nozzle to station 9. At this station, the total temperature is the same as in station 5, but the static temperature has reduced, coming closer to the freestream temperature, but still hotter.

2.2.2 Solid Rocket

All rockets contain both fuel and oxidizer within the rocket. According to Mattingly, the ideal thrust of a rocket is the difference between the internal forces generated by the rocket and external forces working against the rocket. After much derivation, the ideal rocket thrust Th_i can be shown in Equation 6 [15]. For a more in depth derivation of this equation, the reader is encouraged to read [15].

$$h = \dot{} \quad - (\quad - \qquad\qquad) \qquad \text{Equation 6}$$

While most rockets are designed to fly into or in space, the rockets that the author plans to use on the Rossy wingsuit won't. As stated earlier, the rockets that will be used will use a solid rocket configuration, which will be presented here.

Figure 5 shows a simplified, 2-D version of a solid rocket. Figure 6 shows a more detailed, cut away picture of a solid rocket. According to Mattingly, "the fuel and oxidizer are mixed together and cast into a solid mass called the grain. The grain is usually formed with a hole down the middle called the perforation and is firmly cemented to the inside of the combustion chamber. After ignition, the grain burns radially outward, and the hot combustion gases pass down the perforation and are exhausted through the nozzle" [15].

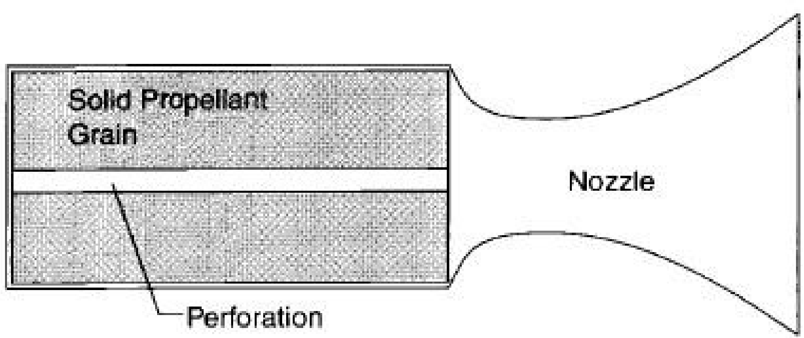

Figure 5. Solid-propellant rocket engine

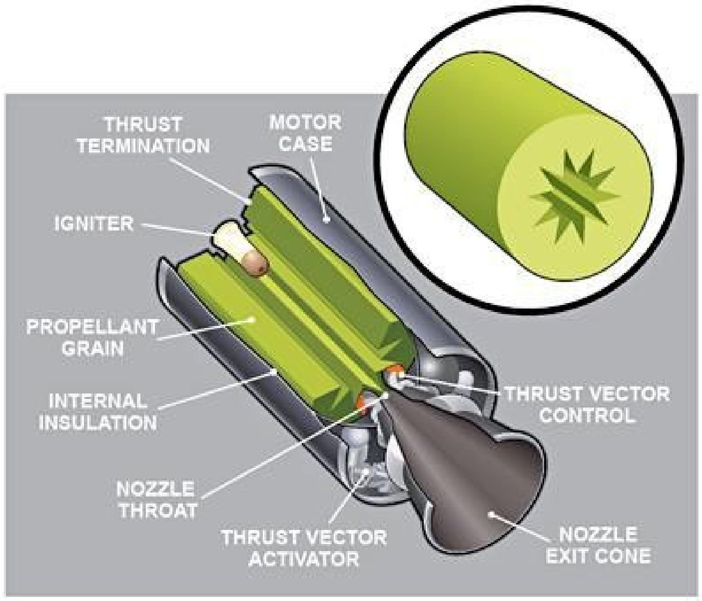

Figure 6. Cut away picture of a solid rocket and its components

2.3 Takeoff Mechanics

With the primary focus of this analysis being focused on ground take off capabilities of the Rossy wingsuit, knowledge of takeoff mechanics is needed. Anderson gives an equation that estimates the takeoff distance needed for an aircraft, and is shown in Equation 7, while Equation 8 shows the velocity needed to take off [14].

$$= \frac{1.44^{2}}{\infty\{h - [\ + (\ -\ )]\ \}} \qquad \text{Equation 7}$$

$$= 1.2\sqrt{\frac{}{\ ^{2}}}\ \infty \qquad \text{Equation 8}$$

Anderson goes on to simplify and equations, and make assumptions about [D + μ_r(W-L)]$_{ave}$, and further reduces the takeoff distance to Equation 9.

$$= \frac{1.44^{2}}{\infty\, h} \qquad \text{Equation 9}$$

Anderson states that equation 9 shows that “1: Lift-distance is very sensitive to weight of the airplane, varying directly as W^2. If the weight is doubled, the ground roll of the airplane is quadrupled. 2: Lift-off distance is dependent on the ambient density ρ_∞. If we assume that thrust is directly proportional to ρ_∞, as stated in Sec 6.7 (earlier in Anderson’s Flight Mechanics book), that is, $T \propto \rho_\infty$, then equation 9 demonstrates that $S_{LO} \propto 1/\rho_\infty^2$. This is why on hot summer days, when the air density is less than on cooler days, a given airplane requires a longer ground roll to get off the ground. Also, longer lift-off distances are required at airports which are located at higher altitudes (such as Denver, Colorado, a mile above sea level). 3: The lift-off distance can be decreased by increasing the wing area, increasing the C_{Lmax}, and increasing the thrust, all of which simply make common sense” [14].

2.4 Gliding Mechanics

Anderson explains that when a plane has its engines off and is in a gliding state, the pitch angle θ can be found using Equation 10 [14].

Equation 10

$$\theta = \frac{1}{/}$$

Anderson also explains that the velocity achieved during gliding flight can be calculated using Equation 11[14].

Equation 11

$$_\infty = \sqrt{\frac{2}{_\infty}}$$

To find a full derivation of these equations, it is recommended that the reader read [14].

3.0 The Rossy Wingsuit

Due to the proprietary nature of the Rossy Wingsuit, limited information is available. Several attempts were made by the author to contact Capt. Rossy and his team directly via email, but those emails were never answered. Thus, the analysis done on the Rossy wingsuit has been performed based on the information that has been made public.

3.1 Known Parameters of the Rossy Wingsuit

According to the Jetman Dubai website, the current Rossy wingsuit has a wingspan of 2 meters, [17]. During a TED talk in 2011, Rossy stated that wingsuit is 55 kg when filled with fuel [18]. The wingsuit has a cruise speed of 200 km/hour, a diving speed of 300 km/hour, and a climb speed of 180 km/hour. The wingsuit has a total flight time of 6 to 13 minutes [17]. All of these stats can be seen in Figure 7. There is one mistake on the Jetman Dubai website: according to the graphic shown in Figure 7, the wingsuit generates 22 kg of thrust. This is incorrect. Thrust is measured in Newtons, which is the product of mass and acceleration using standard SI units. According to the Jet Cat website, each P200-SX engine has a max thrust of 52 lbs, or 231.31 N. Therefore, four P200-SX engines would generate 208 lbs of thrust, or 925.23 N.

Figure 7. Specifications from the Jetman Dubai website [17]

Another design note: the Jetman Dubai website stated in 2011 that the wingsuit had a wingspan of 2.4 meters. According to Figure 8, which was retrieved in February of 2015, the wingspan is 2 meters. After watching several Rossy flights, one conjecture for the reduction in wingspan is that Rossy has recently been performing more acrobatic maneuvers, whereas before he was showing off how far his wingsuit could fly. From 2007 to 2011, Rossy was flying around Mt Fuji, across the English Channel, and flown with F-14 fighter jets in formation, all of which require very high lift capabilities. In 2015, Rossy was performing more acrobatic maneuvers over the city of Dubai, as seen in the YouTube video titled Jetman Dubai: Young Feathers 4K. The shorter wingspan would make the acrobatic maneuvers much easier to perform. The earlier wingsuit can be seen in Figure 8.

Another change in the wingsuit came with the longitudinal length of the wingsuit. Along with the longer wingspan, the wingsuit was also shorter from leading edge to the trailing edge; leaving Rossy's shoulder's exposed. Now, Rossy's wingsuit has the leading edge more forward, covering his shoulders. This can be seen when comparing the wingsuits in Figure 7 and Figure 8.

3.2 Assumptions and Analysis

3.2.1 Assumptions

The weight of Yves Rossy is not published on any known article or website, due to his wingsuit gathering the attention of any journalist writing about him. As such, a height and weight of 160 lbs. and 5'10" will be assumed for the pilot for aerodynamic analysis purposes. Using visual approximations reveals a 17^{o} wing sweep. For a more in depth look at the handwritten work and constants used, see appendix A. Also, the earlier version of the wingsuit is favorable when it comes to lift and take off, so the analysis will be performed on the wingsuit in Figure 8.

Figure 8. Rossy Wingsuit, circa 2008.

3.2.2 Aerodynamic Analysis

During cruise, and assuming max weight, L=W and D=Th, thus L = 160lbs + 55kg*2.2 = 281lbs, and at max thrust, D = 208 lbs. The lift to drag ratio, or L/D, is then found to be 281lbs/208lbs = 1.35. Equations 4 and 5 can be used to find the coefficient of lift and drag for the wing. With a planform area S of 1.2742 m^2, and assuming an altitude of 8,000 ft. during cruise, C_L=1.208 and C_D=.895. With a wingspan of 2.4 meters, the wingsuit has an AR of 4.52.

3.2.3 Takeoff and Gliding Mechanic Analysis

Using Equation 8 is difficult to use in this case. As mentioned earlier, the proprietary nature of the Rossy wingsuit prohibits information from being made public. The C_{Lmax} of the wingsuit is not known to the author, so finding the minimum velocity needed for this wingsuit to takeoff can't be found at this time. However, with the AR = 4.52, and using Figure 2; C_{Lmax} can be seen to be somewhat high.

Equation 7and Equation 9 show that the higher the thrust, the shorter the takeoff distance. These equations form part of the basis of this report, and using the thrust of the solid propellant rocket would allow for a shorter takeoff distance. However, these equations prove difficult to use due to being dependent on C_{Lmax} of the wingsuit.

As mentioned earlier, Rossy jumps out of an airplane and enters a gliding phase before beginning flight. Equation 10 and Equation 11can be used to find the gliding velocity of the Rossy wingsuit. If L, C_L, and D are assumed to be at their cruise values (281 lbs., 1.208, and 208 lbs., respectively), then V_∞ comes out to be 95.895 mph. See Appendix A for the handwritten work on how this value was found. This does not mean that Rossy waits until V_∞ = 95 mph to turn on the jet engines in order to achieve flight, nor does it mean that while gliding, the lift, C_L, and drag values are 281 lbs., 1.208, and 208 lbs., respectively. This just gives a starting point for analysis. As stated earlier, analysis of a model would provide better approximate data, and give better values for gliding velocity.

4.0 Future Work

Future work would include the production of a model of the Rossy wingsuit, and using that model to gather wind tunnel data that would closely approximate the actual Rossy wingsuit, and being able to use equations 7, 8, and 9. Research into the size the type of solid propellant rocket to be used for takeoff is also necessary: rockets available, parametric study to find which rocket is best and analysis of takeoff using the chosen rocket are next tasks to be completed.

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Appendix A

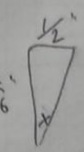
old design

New

me { Bottom delt to knee ish $26\frac{1}{2}$ — $35''$

Chest (no shoulders) width : $16\ \frac{1}{2} = 41.91$ cm

Proportion : .384 26.7



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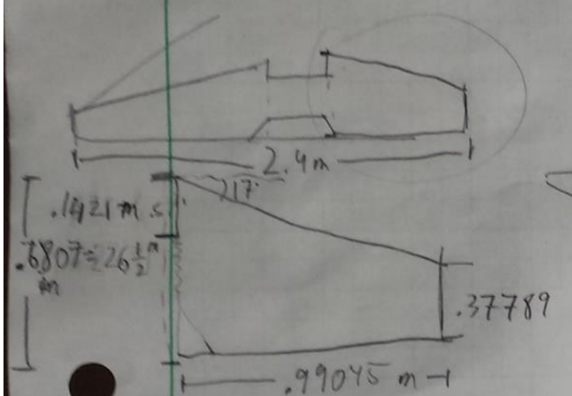

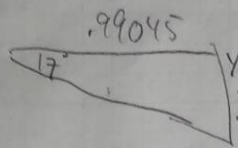

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$.5386 \cdot .4191 = .2257\ m^2$

$C_L = \frac{L}{\frac{1}{2}\rho V^2 S} = \frac{281\ lbs}{\frac{1}{2} \cdot .5258\frac{kg}{m^3} \times 124.274\,mph^2 \cdot 1.2742\,m^2}$

$= \frac{1249.95\ N}{\frac{1}{2} \cdot .5258 \cdot 55.56^2 \cdot 1.2742} = 1.208 = C_L$

$C_D = \frac{208}{} = \frac{925.23}{} = .895 = C_D$

$AR = \frac{2.4^2}{1.2742} = 4.52$

$\tan\theta = \frac{1}{281/208}$ $\theta = 53.49°$ $V_\infty = \sqrt{\frac{2\cos\theta}{.5258 \cdot 1.208}\ \frac{1249.95\,N}{1.2742}}$

42.869 m/sec

95.895 mph

V_∞