MODELING AND PERFORMANCE ESTIMATION OF FORMATION FLIGHT

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STATEMENT OF ORIGINALITY

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution.

______________	_______________________
Date	M. Shakeel Awan

Dedication

I dedicate this effort to all those who have assisted me in any possible way to become what I am today. Their sacrifices seeded my success especially my parents who showed their devoted attention and to faculty members who inspired me all the way.

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Abstract

The aviation industry has grown tremendously during last fifty years. The number of commercial airliners has doubled over the past decade, however, a proportional increase in the environmental degradation is also observed. At present, the contribution of commercial aeronautics to the carbon footprint is approximately around 2%. This poses a great challenge for technology protagonists. The development of stringent emission regulations is forcing the commercial aeronautics community to search for alternate / optimized ways of flying. Moreover, for small UAVs, on-board fuel storage is a big challenge because of dimensional / weight constraints. Such constraints are a cause of significant hindrance in performance of small UAV's. The solution to both these domains comes from nature inspired observation of migrating birds. They travel across the continents in formation flight and recent research findings show promising benefits of formation flying for man-made aircrafts. Introducing formation flying in commercial aviation can result in cost savings and reduce environmental degradation. This effort takes into account the opportunities provided by formation flying and present an optimized hybrid formation switching mechanism for enhanced range and endurance of commercial aviation as well as small UAVs. This thesis adopts a two prong approach and tries to discuss a common solution to different problems of commercial aeronautics and Unmanned Air Vehicles (UAVs).

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List of Abbreviations

CO_2	Carbon Dioxide.
R&D	Research and Development.
UAV	Unmanned Air Vehicle.
WTS	Wing Tip Spacing.
NASA	National Aeronautics and Space Administration.
DARPA	Defence Advanced Research Projects Agency.
DOF	Degree of Freedom.
SP	Switching Point.
COG	Center of Gravity.
AR	Aspect Ratio.
SFC	Specific Fuel Consumption.
CL	Lift Coefficient.
CL_L	Lift Coefficient of Leader Aircraft.
CL_W	Lift Coefficient of Trailer Aircraft.
CD	Drag Coefficient.
ΔCL	Change in Lift Coefficient.
ΔCD	Change in Drag Coefficient.
a_w	Lift Slope.
S	Surface Area.
b	Wingspan.
L	Lift.
W	Weight.
L/D	Lift to Drag Ratio, Aerodynamic Efficiency.
M	Mach Number.
e	Oswald Factor.
Ah	Battery Ampere Hours.
n	Battery Discharge Parameter.
Rt	Battery Hour Rating.
C	Battery Capacity.
ρ	Air Density.
ft	Feet.
lbf	Pound-Force.
NM	Nautical Miles.

CHAPTER 1

INTRODUCTION

Commercial aviation industry is bound with regulations set by the governing bodies /authorities. Fuel efficiency and carbon-dioxide (CO_2) emissions are the most stringent requirements for aircraft certification and air worthiness. A key component to meet such requirements is engine which works on the principle of internal combustion. The compressed air is burnt with the fuel at high pressure and temperature which causes the exhaust of hot gases at higher pressure providing the necessary thrust to an aircraft. Exhaust gases contain large quantities of CO_2 which are undesirable because of having a degrading effect on earth's atmosphere. The contribution of commercial aeronautics to the carbon footprint is approximately around 2% [1]. Aircraft manufacturers like Boeing®, Airbus® and Bombardier® neither design nor develop jet engines instead they opt for commercial-off-the-shelf solutions from leading manufacturers such as General Electric®, Pratt & Whitney® and Rolls Royce®. Since the design and development effort to meet the emission regulations takes years of planning, R&D, specialized skills and trained manpower, therefore such solutions are costly. Comparatively, an electric propulsion system, which includes an on-board battery pack, has a reduced degrading effect on the environment. The storage capacity of such a battery pack is constrained hence the flying object has a limited flight time and the generated thrust is low. Thus, the electric propulsion system is unable to power an aircraft weighing tons as the thrust required is in excess of thousands of Newtons. However, as a typical small UAV may weigh only a few kilograms, therefore, electric propulsion is best suited for UAVs. Such low weight devices come at a price i.e. decreased performance caused by geometric and dimensional issues. Physics which governs the performance of large body commercial aircraft or small UAV is fundamentally the same. An onboard propulsion system provides thrust to overcome drag and wings providing lift to carry aircraft / UAV weight. Consequently, an aircraft has a limited flight range and UAV has limited flight endurance. This effort focuses on extending the range and endurance for an aircraft / UAV using existing solutions widely adopted within aviation industry.

1.1 MOTIVATION

Wing airfoils are so designed that the air flow at the top surface is at a higher airspeed and low pressure (**Bernoulli's principle**) as compared to the flow underneath the airfoil. The pressure difference between the two surfaces generates the necessary lift for an aircraft. However, as the airflow at higher pressure region spills towards region of low pressure i.e. from bottom to top of the wing, a vortex is formed at the tip of each wing. The vortex is a powerful circular airflow and is left behind as the aircraft travels. Two prominent fields are downwash, which is a higher pressure region under the wing, and upwash which is a region of the vortex at each wingtip as depicted in Figure 1.1.

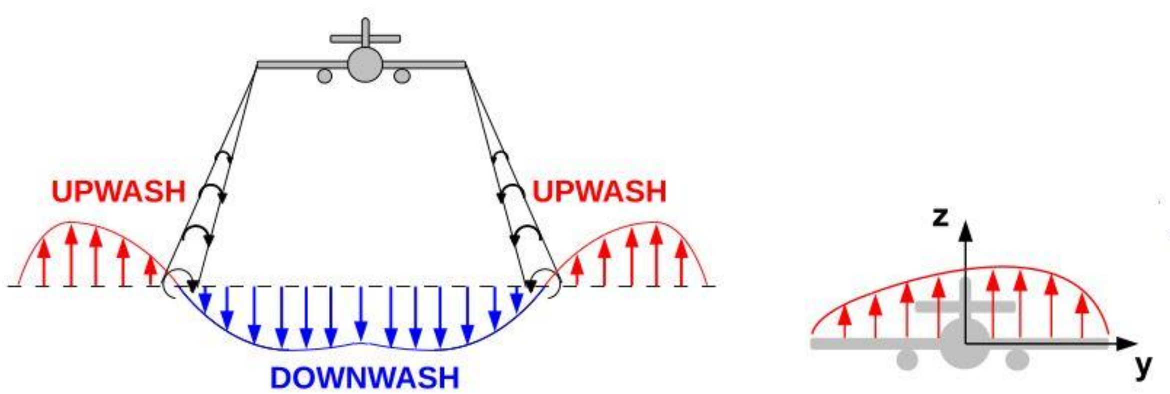

Figure 1.1: Downwash and Upwash Fields [11].

Consider two aircrafts flying in formation involving a leader and follower. Placing the follower aircraft in the upwash region will provide it with an additional lift that helps improve aircraft's aerodynamic efficiency. Since aircraft performance parameters depend on its aerodynamic efficiency, thus at higher aerodynamic efficiency an aircraft can attain higher performance.

1.2 AIRCRAFT PERFORMANCE PARAMETERS

Range and endurance are two key parameters of the aircraft performance. Range is a measure of distance flown between takeoff and landing measured in kilometers while endurance is the maximum duration of time that an aircraft spends during its flight measured in hours.

A typical aircraft is powered by a propulsion system which may consist of either a jet engine or a battery pack. An aircraft / UAV can only fly with a limited amount of propellant on-board which is governed by aircraft's geometric parameters. For an aircraft that can store more fuel shall have more flight duration. Performance parameters not only depend on fuel capacity but also on several other parameters including aerodynamic efficiency (lift / drag), flight altitude and other geometric parameters i.e. weight and surface area.

In formation flight, aerodynamic efficiency of the trailing aircraft can be improved which results in higher performance. Using this fact, in this research we analyze the improvement in two parameters of aircraft performance in formation flight namely range and endurance.

1.3 INTRODUCTION TO CURRENT RESEARCH

We propose a nature inspired solution to enhance aircraft performance in both domains i.e. commercial aeronautics and UAVS. Flocks of birds travel long distances in formation. In formation, birds place themselves in upwash region of each other starting from the formation leader. In doing so the follower bird experiences an improved aerodynamic efficiency. The efficiency improvement is justified for power saving among flocks and lower heartbeat compared to solo flight, which results in collective flying for thousands of miles. Same concept is exploited for commercial aviation and small UAVs in this research. First, a parametric study of formation flying is carried out for the benefit of range and endurance of aircraft / UAV. The effects of lateral and vertical spacing, among formation leader and follower aircraft, on range and endurance are investigated. Next, we study the fuel consumption at the optimal spacing to figure out the maximum fuel saving. Major novelty of this research is to present benefits of flying in a hybrid formation along with a mechanism for leader-switching.

1.4 RESEARCH OBJECTIVES

Following are the objectives of current research:

- **Parametric Studies of Formation Flying**
    - Lateral Spacing effect on Jet Aircraft Performance.
    - Vertical Spacing effect on Jet Aircraft Performance.
    - Lateral Spacing effect on Battery Powered UAV Performance.
    - Vertical Spacing effect on Battery Powered UAV Performance
- **Fuel Consumption Studies.**
    - Individual Vs Formation Fuel Consumption
    - Fuel Savings per Passenger per 100 KM.
- **Formation Switching Mechanism.**

1.5 THESIS ORGANIZATION

This thesis is organized as follows. Chapter 1 gives a background on fundamental challenges in aircraft performance of commercial aviation and small UAV's. It highlights the motivation and research objectives of this research and introduces the proposed solution. In Chapter 2, we present a structured analysis of existing work carried out in formation flying. Our proposed method is discussed in detail in chapter 3. In chapter 4, the results obtained by designing an algorithm based on proposed model are illustrated along with a discussion. The thesis concludes in Chapter 5 where recommendations are suggested for future work.

CHAPTER 2

LITERATURE REVIEW

Over the years, efforts have been exerted to better analyze and understand underlying concept and the working principles of bird's formation flight and its application in the aviation industry. Following is a summary of existing work carried in this regard.

2.1 BIOLOGICAL STUDIES OF FORMATION FLYING

Formation flying has captured attention of biological scientists and experts in aerospace industry for years. For a bird to fly, it requires lift which it gets by flapping its wings. The power required for producing the said lift is called induced power. Induced power is different from profile power which is the power required to fly through air and overcome skin friction. Induced power saving is the most prominent benefit birds achieve in formation flight.

A study of induced power saving by Hainsworth [2] was carried out in 1986. The author studied 55 different sets of Canadian Geese flying in V-formation to test savings in induced power. Bird formation flight was modeled by placing the follower birds' wing in a vortex field generated by leaders' wings. The author analyzed measurement of wing tip spacing (WTS) among the bird formation. The study estimated that on average the WTS corresponds to 36% induced power saving. Lissaman and Shollenberger [3] adopted an aerodynamic model of formation flight in birds and their associated aerodynamic efficiency to establish an analogy for fixed-wing aircrafts from standard wing theory and compared the induced drag in formation with solo flight. A formation of 25 birds in V-formation resulted in range enhancement of 71% compared with solo flight.

Traditionally these studies were restricted to the steady aerodynamics of rigid body. David et al. [4] investigated optimal energy saving schemes in flapping-wing flight. They examined non-steady vortices of lead bird and their interaction towards energy saving within migrating formation and found that the region of energy saving for trailing bird was outboard of wingtips of leader bird. It was also found that a greater upwash was produced by the leader's down-stroke due to which the follower bird benefited even more.

2.2 FORMATION STUDIES IN AIRCRAFTS

Encouraging results from biological scientists motivated aerospace experts to test aircraft formation flying benefits. Many studies of aircraft in formation have been conducted experimentally where drag reduction and fuel saving remained the focal point. Experimental studies being the expensive option to test formation benefits were conducted by leading aerospace organizations. A NASA funded project by Ray et al. [5] estimated the performance benefits at NASA's Dryden Flight Research Center by flying two modified F/A-18 aircrafts in an experimental formation. F/A-18 is a military fighter aircraft powered by two General Electric F404-GE-400 engines each producing 16,000 lb_f of thrust. Experiments concluded that at an altitude of 25,000 ft and a speed of 0.56 Mach results in a 20% drag reduction and a fuel flow reduction by 18%. Another experiment was conducted in cruise conditions at 40,000 ft at 0.8 Mach which demonstrated 14% fuel reduction. While F/A-18 is a military fighter aircraft with a relatively small wingspan of 37 ft, some studies were also carried out for larger and heavier aircrafts. Sponsored by DARPA, Blake et al. [6] undertook a fuel benefit study in a formation of two C-17A, a military air transport aircraft of wingspan 165 ft. In this study longitudinal separation was fixed at 3000 ft and lateral spacing was varied from 150 – 250 ft. Maximum fuel advantage was recorded at minimum lateral spacing of 150 ft where 9% fuel benefit was recorded.

Another aspect that relates to formation flying is the spacing among the aircrafts participating in the formation. Maximum benefits can be achieved by harvesting maximum wake at close proximity, however, the safety of the aircraft is compromised at such close distance. Hence, it is vital to identify effects of maintaining accurate spacing between the lead and the trailing aircraft. Blake and Multhopp [7] explored aspects of accuracy in maintaining lateral position and relative range in formation of F-16's fighting falcon. In cruise conditions, the range increased by 60%. Their study focused on benefits lost if spacing accuracy was not maintained. 50% drag benefit is lost if lateral and/or vertical position is not maintained better than 1/10th of a wing span. Dijkers and Nunen [8] investigated formation flight for commercial airlines aimed at reducing emissions and increasing fuel efficiency. The numerical simulation for Boeing 747-8 concluded a 54% fuel burn savings at 10 wingspans longitudinal spacing.

2.3 THEORETICAL STUDIES OF FORMATION FLYING

In addition to experimental studies few theoretical studies have also been conducted. Kniffin and Dogan [9] of US Air Force Research Laboratory developed a 6-DOF simulation model to investigate fuel savings in a formation of KC-135R as leader and F-15 C/E as trailer aircraft. KC-135R is a midair refueler (tanker) whereas F-15 is a fighter aircraft. The results showed 14% thrust reduction which was found to be proportional to the leader's weight. Understanding the effect of leader's geometry on trailer's aerodynamics is the fundamental concern of Pachter et al. [10]. He modeled the effect of aerodynamic coupling on the wingman by placing aircrafts in close proximity. The mathematical derivation is inspired from electromagnetism as an analogy of current in electric wire which produces an electric field in its vicinity. As a result the model presents ‘change in lift, ΔCL’ and ‘change in drag, ΔCD’ as a function of lateral and vertical spacing between the leader and trailer aircraft at close proximity. It is worthy to mention that the trailer’s change in aerodynamic coefficient is influenced by the leader’s lift coefficient. So this model can yield trailer’s lift and drag coefficients at any lateral or vertical spacing between aircrafts. This thesis uses these coefficients to estimate the performance of the trailing aircraft. A greater insight to this model is presented in Chapter 3.

Formation flying leads to improve aerodynamic efficiency however it is critical to predict the leader’s wake. In his effort, Hemati et al. [11] established a strategy for wake sensing and estimating its position in a two ship formation. Reliable wake estimation was taken from wing-distributed on-board sensors. The wake leaves an aerodynamic signature on the trailing aircraft and the proposed strategy can point out wake position and nonlinearity associated with it. Multiple nonlinear filtering algorithms were invoked to predict wake behavior which include Kalman-type and Particle filtering. DeVries and Paley [12] also adopted a similar approach towards investigating relative wake position in two different cases of two-aircraft, i.e. formation flight and autonomous air refueling, by invoking Bayesian estimation of leader’s wake parameters. The authors also designed an optimal control strategy for follower aircraft to position itself in the wake of its leader.

2.4 AIRCRAFT’s RANGE AND ENDURANCE

Aircraft manufacturers strive to provide best solutions to commercial aviation. Airlines choose economic options from wide variety of available choices. Range and endurance are aircraft’s most dominant performance parameters and tend to influence aircraft selection decisions. Hence aircraft manufactures rely on means by which a detailed performance insight can be realized. One such means of aircraft performance estimation is the Breguet range equation which is influenced by aircraft propulsion, aircraft design and structural details. The same equation is realized by Bert [13] in estimating maximum range of a jet aircraft at constant altitude and determining optimum airspeed. Aircraft's aerodynamic efficiency (L/D) in formation is improved so is its range as has been proven by Ning et al.[14]. They evaluated the drag saving benefit in a two- and three-aircraft formation where the induced drag was reduced by 26-31% and 38-45% at separation of 20 span, respectively.

Endurance on other hand is an important performance parameter of UAVs. The electric powered nature of a UAV defines its stealth characteristic. Traub [15] estimated the range and endurance models for small electric powered unmanned aircrafts. A critical parameter effecting performance of electric powered UAVs is battery capacity i.e. a measure of rate at which it is discharged. For a battery with capacity of 1C means battery will discharge in 1 hour. A higher range and endurance of electric powered UAV is obtained with a battery of higher capacity. A detailed glimpse of range and endurance models is discussed in chapter 3. Pachter's aerodynamic model of predicting change in lift/drag coefficient of a UAV in the leader's wake is adopted to investigate performance benefits.

2.5 MISSING LINK IN LITERATURE

Comprehensive work has been carried out by aerospace organizations / aerospace experts in the domain of formation flying. However, some aspects are still needed to be explored. Leader's wake is a function of strength at a particular spacing hence, the trailing aircraft's performance would be dependent on formation spacing (more the wash is stronger, more the lift is induced).

Therefore, there is a need to capture parametric effects on aircraft performance i.e. lateral and vertical spacing. Furthermore, in this literature review we have established that fuel burn saving is a key benefit of formation flight. Thus, a parametric study is essential to model the fuel burn saving as a function of formation spacing.

The leader aircraft plays a vital role in formation flight. Its job is to provide wash for the trailing aircraft to place itself carefully and get aerodynamic benefits. Another missing link in literature is the determination of formation switching-point at which the roles should reverse (leader to switch with trailer) so that equal benefits are harvested for the formation as a whole. A study is to be carried out with an objective to discover a switching-point, which should ensure equal extension of range for both aircrafts from their designed range (manufacture's quoted range).

UAV's are usually not considered to be flown in formation and no such study exists in literature to the best of our knowledge. Small UAVs face strong on-board fuel constraint due to their small size and dimensions. Such constraints significantly limit their performance (range and endurance). A formation parametric study is to be carried out to investigate the performance of a small UAV and highlight the gains.

CHAPTER 3

METHODOLOGY AND COMPUTATIONAL SETUP

A particular flight envelope originates from takeoff, climbing, cruise, descend and landing. Cruise may constitute up to 90% of flight and is the main leg of flight envelope where aircraft spends most of its flight time due to the fact that in cruise condition aircraft flies at maximum aerodynamic efficiency $\left(L/D\right)$max . A major proportion of fuel is burnt in cruise where drag is minimum and travel is considerably economical. Aircraft manufactures estimate performance of an aircraft in cruise since it gives a detailed insight into an aircraft's performance. In this research, the problem of formation flight is studied in cruise phase. First, it is safer to fly in formation while cruising compared with other phases such as takeoff, climb, descend, and landing where aircraft safety is a major concern. It is also simpler to model the aerodynamic coefficient in this phase of flight as compared with other phases which are highly dynamic. A detailed note on aircraft safety in formation is discussed in Chapter 5.

This work constitutes three portions briefly explained below:

1. **Aerodynamics** of a trailing aircraft is considerably dissimilar to its leader. Wake of leader leaves aerodynamic signature on trailer aircraft. This wake rotates its lift vector forward which in turn reduces the induced drag and significantly improves its aerodynamic efficiency. Figure 3.1 shows the vortex of an aircraft. In formation, the trailer aircraft's wing is carefully placed in this vortex to experience a reduction in induced drag. This reduction is caused by incoming air's rotation for trailer's wing and increased speed of incoming air for trailer's wing.

Figure 3.1: Aircraft Vortex System [8].

Incoming air induces additional force on the trailer's wing which rotates its drag and lift vector. This part explains Pachter model of aerodynamic coefficients influenced in formation flying also parameters such as lateral and vertical spacing on performance parameters of aircraft.

2. **Performance** is dependent on an aircraft's geometry, propulsive and aerodynamic efficiency. Aerodynamic efficiency in cruise is a fixed quantity for an aircraft. However, in formation, aerodynamics is significantly improved so is the performance of the trailing aircraft. This portion evaluates range and endurance enhancement based on the aerodynamic model. Range is an imperative parameter of a commercial aircraft whereas endurance is a critical performance parameter of a UAV.
3. **Leader-switching** section focuses on a strategy to switch the leader with the follower aircraft. In formation, the follower aircraft gets benefit from leader's wake. At some point in cruise, follower aircraft must switch to become leader so that benefit is shared equally within a formation. A switching-point (SP) is therefore to be determined where formation roles must switch. Proposed approach is to determine best SP describe required fuel burn of leader as leading role while trailer's fuel saving is to be determined in trailing role because it is flying at higher aerodynamic efficiency. After switching formation roles, the new-leader flies at lower aerodynamic efficiency nonetheless it has more fuel onboard whereas new-trailer has less fuel but flies at higher aerodynamic efficiency. Finding the

fuel burn required by leader as leading role and then switch with trailer for which consequently total formation range is equally extended is addressed in this part.

3.1 AERODYMANIC MODEL IN FORMATION

The mathematical model of formation flight proposed by Pachter, reshapes lift and drag coefficients (CL, CD) for trailing aircraft influenced by up-wash. The model was derived to understand aircraft stability and control in tight formation. Our effort intends to use this model in evaluation of aircraft performance in formation.

3.1.1 CHANGE IN LIFT COEFFICIENT

Incoming up-wash rotates lift vector which in turn changes lift profile of aircraft. Following equation evaluates change in lift coefficient (ΔCL) from leader's wash.

$$\Delta CL_w = \frac{a_w}{\pi * AR} * CL_L * \frac{2}{\pi^2} * \left\{ \ln \frac{y'^2 + z'^2 + \mu'^2}{\left[y'^2 - \left(\frac{\pi}{4} \right) \right]^2 + z'^2 + \mu'^2} - \ln \frac{\left[y'^2 + \left(\frac{\pi}{4} \right) \right]^2 + z'^2 + \mu'^2}{y'^2 + z'^2 + \mu'^2} \right\} \quad ... 3.1$$

Equation 3.1 can be briefed in two parts. First part is aerodynamics and second is spacing in logarithmic terms. Trailer's lift is influenced by the leader's lift coefficient $(CL_L = L / q * S)$ and is to be determined in cruise condition where aircraft lift equals weight $(L = W)$ and dynamic pressure is $(q = 1/2 * \rho * V^2)$ at cruising altitude and Mach number. Lift Curve Slope a_w is the change in lift w.r.t to change in angle-of-attack and can be estimated by:

$$a = \frac{a_0}{\sqrt{1-M^2} + (a_0 / \pi e AR)} \quad ...\ 3.2$$

Lift curve slope is a function of the Mach Number (M), Oswald factor (e), Aspect Ratio (AR) and $a_0 = 2\pi$. Logarithmic terms in equation 3.1 concern with the spacing in formation. Lateral spacing y' is the formation spacing on y-axis from center of gravity (COG) of aircrafts. Vertical spacing z' is formation spacing on z-axis from COG. Vortex core radius μ' is associated with leader's wingspan. In literature vortex radius is estimated to be up to 7% of aircraft wingspan [16]. y', z', μ' are non-dimensional quantities being non-dimensionalized w.r.t to leader's wingspan. Furthermore, it can be visualized that spacing between formation has a greater influence on the trailer's lift.

3.1.2 CHANGE IN DRAG COEFFICIENT

Incoming up-wash also affects the trailer's drag vector. This effect is captured by the following equation:

$$\Delta CD_W = \frac{1}{\pi * AR} CL_L CL_W \frac{2}{\pi^2} \left\{ \ln \frac{y'^2 + z'^2 + \mu'^2}{\left[y'^2 - \left(\frac{\pi}{4} \right) \right]^2 + z'^2 + \mu'^2} - \ln \frac{\left[y'^2 + \left(\frac{\pi}{4} \right) \right]^2 + z'^2 + \mu'^2}{y'^2 + z'^2 + \mu'^2} \right\} \quad ...\ 3.3$$

All parameters except the trailer's lift coefficient CL_W in the above equation are same as those in cruise condition. Gradual increase in lateral and vertical spacing should reflect wavering lift and drag coefficients consequently performance should vary as a function of formation spacing.

3.1.3 LIMITATION OF AERODYNAMIC MODEL

The adopted model captures the underlying variables in formation flying i.e. lateral spacing and vertical spacing. However, the only limitation of this model is that it doesn't realize longitudinal spacing between aircrafts. This is due to the fact that the author has modeled the up-wash using an analogy with electric strength produced by current in electromagnetism disregarding the longitudinal component due to infinite length. Hence, the effects captured at any particular lateral / vertical spacing should hold at infinite longitudinal spacing. Realistically it is untrue as the wake is dissipated in atmosphere and decays as a function of time and distance. A study at NASA Langley Research Center, Virginia by Proctor et al. [17] was conducted to examine vortex decay in turbulent and stratified atmosphere. It suggested that the decay of vortex over time is a phased process as shown in Figure 3.2. Sarpkaya noted that vortex lifetime is dependent upon intensity of ambient and turbulence i.e. strong turbulence results in shorter vortex lifetime.

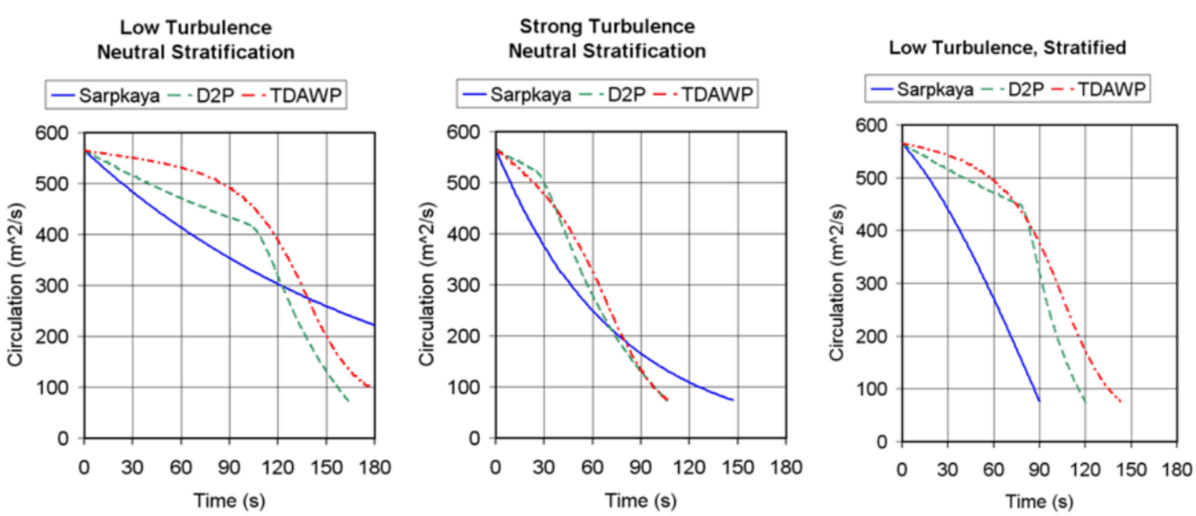

Figure 3.2: Phased Decay of Vortex [17].

Deterministic 2-phase (D2P) and TASS Driven Algorithm for Wake Prediction (TDAWP) model suggests that the decay of vortex in first phase is a linear process where decay is weak over time while a non-linear decay follows where decay rate is rapid.

The results drawn from these models suggests that a wake 30 second old for a Boeing 747 class aircraft is still 90% strong which accumulates longitudinal spacing of 8000 meters approximately. These results are a good omen to our problem statement and shortcoming of the aerodynamic model. An aircraft within first phase of decay, where vortex is strong enough, reflect a positive performance on trailer's aircraft. Under a DARPA funded program, an experimentation flight of two C-17'A with longitudinal spacing of 18 wingspans resulted in 9% fuel savings. This study suggests that the wake at 3000 feet spacing is still powerful which can result in fuel burn savings. Although, the accuracy of longitudinal spacing cannot be ensured but it can be confidently said that performance at a particular lateral or vertical spacing should hold anywhere within the vortex first decay phase (a 30 seconds gap between leader and trailer).

3.2 PEFORMANCE MODEL

Range and Endurance are performance parameters of any aircraft. Performance model of a jet-powered aircraft is significantly dissimilar to that of a battery-powered UAV. Working principles of both propulsion systems are different too. In this section, the performance model adopted to evaluate range and endurance is briefly explained.

3.2.1 RANGE OF JET POWERED AIRCRAFT

Range is a measure of distance flown between takeoff and landing measured in kilometers. It is a design and performance parameter of an aircraft. Breguet first modeled the range of jet-powered aircraft and expressed it as:

$$Range = (\frac{V}{SFC}) * (\frac{L}{D}) * \ln\left(1 + \frac{W\_Fuelused}{W\_Empty + W\_Payload + W\_\mathrm{Re}serve}\right) \quad ... 3.4$$

Range of a jet powered aircraft depends on propulsion design (SFC), aircraft design (L/D) and structural design (W). In this model velocity is given in knots (converted from cruising Mach number), weight in pounds (converted from kilogram) and SFC is given in $(lb/h)/lbf$. Nautical miles are to be converted in kilometers (1NM = 1.852 KM).

3.2.2 RANGE AND ENDURANCE OF BATTERY POWERED UAV

Range and Endurance of small battery-powered UAV is given by:

$$Range = Rt^{1-n}\left\{\frac{\eta_{tot} * V * C}{\left(\frac{1}{\sqrt{\rho S}} * (CD_0)^{\frac{1}{4}} * (2W\sqrt{k/3})^{\frac{3}{2}}\right)}\right\}^n \left\{\sqrt{\frac{2W}{\rho S}\sqrt{\frac{k}{CD_0}}}\right\} * 3.6 \quad ... 3.5$$

$$Endurance = Rt^{1-n}\left\{\frac{\eta_{tot} * V * C}{\left(\frac{2}{\sqrt{\rho S}} * (CD_0)^{\frac{1}{4}} * (2W\sqrt{k/3})^{\frac{3}{2}}\right)}\right\}^n \quad ... 3.6$$

In above equations, $Range$ is given in Kilometers, $Endurance$ in Hours, V in Volts, ρ is the Air Density, S is the wing surface area, C is battery capacity, n is discharge parameter, Rt is the battery rating in hours, CD_0, k are airfoil aerodynamic parameters and η_{tot} is the total efficiency of battery and propulsion system. For maximum range $CD_0 = k * CL^2$ and $CL = \sqrt{\frac{CD_0}{k}}$, whereas for maximum endurance $CD_0 = (1/3) * k * CL^2$. In computation these values are plugged where CL varies as a function of formation spacing.

3.3 FORMATION SWTICHING

A formation has a leader and trailer aircraft where trailer aircraft has an aerodynamic advantage over its leader due to flying in upwash regime. Trailing aircraft experiences additional lift which rotates its lift vector forward hence reducing induced drag. In this section a strategy is to be developed where a leader switching point (SP) is to be determined where the leader switches position with trailer aircraft. This switching point must ensure all-equal aerodynamic benefits for the whole formation i.e. leader gets the same range as trailer.

First, the leader covers a particular distance for which it consumes fuel whereas trailing aircraft covers the same stretch consuming far less fuel because of its higher aerodynamic efficiency. At SP, formation roles are reversed, leader now becomes trailer and gets aerodynamic benefits. New-leader which has saved fuel while trailing now flies at lower aerodynamic efficiency with more fuel available on-board contrary to the new-trailer which has less fuel but now flies at higher aerodynamic efficiency. For evaluation of practical switching point, it is vital to investigate the fuel available on-board with the leader and trailer at SP so that travel distance afterwards ensures equal extension in formation range.

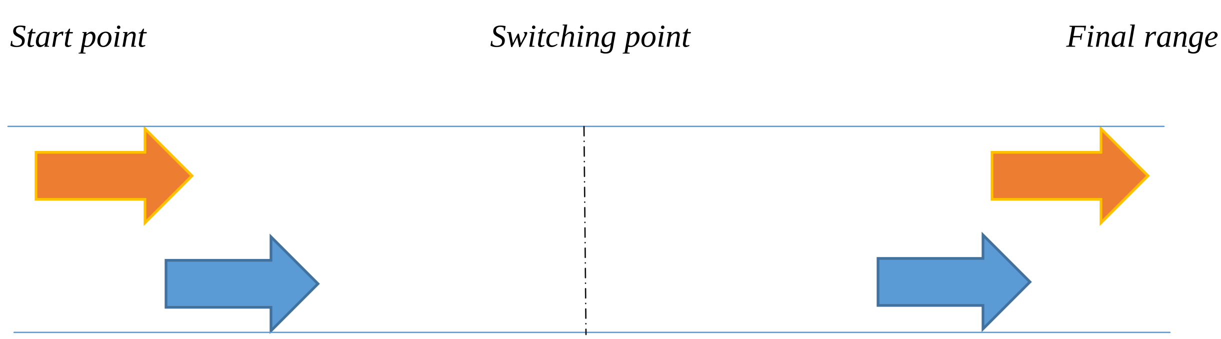

Figure 3.3: Formation Switching

3.4 METHODOLOGY

Figure 3.4 summarizes the methodology of research.

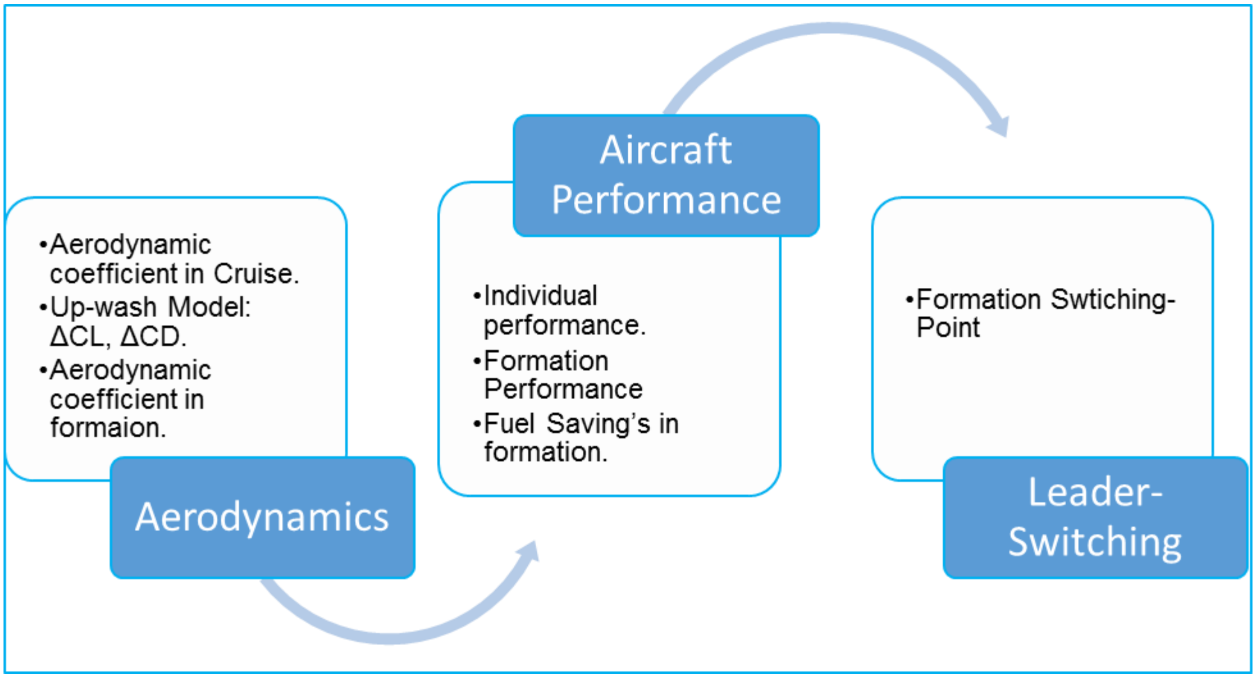

Figure 3.4: Methodology

Aircraft's lift coefficient in cruise phase is given as $CL = L/_{q*S}$ where $q = 0.5*\rho*V^2$. Here, S is the surface area of the wing, ρ is the air density and V is aircraft velocity. In cruise phase, the weight of aircraft equals its lift where velocity is its cruising speed. Aircraft's wing surface area, cursing speed and weight are made available by manufacturers. For a given altitude, aircraft's lift coefficient can be determined.

First, leader's and trailer's lift coefficients (CL_L, CL_W) are calculated in cruise condition and drag coefficients (CD_L, CD_W) are estimated from lift-drag polar. List of aircrafts selected from the project and their lift-drag polar is made available in Chapter 4. Individual aircraft performance is estimated from these coefficients. Pachter Aerodynamic model is invoked to estimate transformation observed in aerodynamic coefficients $(\Delta CL_W, \Delta CD_W)$ in formation.

Unifying coefficients $\left(CL_W + \Delta CL_W\right)$, the lift required in formation can be obtained. As these coefficients are influenced from upwash as a function of formation spacing (y', z'), performance of trailer aircraft at any spacing point can be determined. Performance parameters are a function of aircraft's aerodynamic coefficients; we expect to see a variation on trailer's performance. Trailer's performance is realized as function of spacing $\left(y', z'\right)$.

Straightway, negative impact on the performance is expected at lateral and vertical spacing $\left(y', z' = 0\right)$. This is because at this spacing trailing aircraft shall be in leader's downwash regime where it shall lose critical lift and increase in drag to be observed. However, as lateral spacing increases $\left(y' = 1:2b, z' = 0\right)$ w.r.t. to leader's wingspan (b) at fixed vertical spacing, a positive performance is expected. Similarly, vertical spacing is to be varied $\left(z' = 0:0.5b\right)$ next. A comparison of individual and formation performance needs to be made to understand the optimum spacing points in formation. Optimum spacing point is where trailer shall get the maximum advantage. Same effort is to be carried out on a formation of two UAV's. Once the optimum spacing point is known, a fuel consumption study is in order as it is a function of aircraft fuel and range. As range is expected to increase in formation for same amount of fuel it will be interesting to observe fuel consumption benefits in formation. Lastly, this effort focuses on a leader-switching strategy. A formation SP must be determined where formation roles are reversed so that formation range for both aircrafts are equally extended from their designed range. In this regard, fuel benefits on trailer aircraft are to be closely examined where it flies at higher aerodynamic efficiency and the leader burns more fuel at lower aerodynamic efficiency. At SP, aerodynamic coefficients have to be recalibrated due to the fact that both aircrafts have burned significant amount of fuel and lost proportional weight. After SP both aircraft fly with different fuel profiles, the new-leader flies at lower aerodynamic efficiency and it has more fuel but in this phase consumes more fuel whereas the new-trailer consumes less fuel at higher aerodynamic efficiency but has less fuel on board.

Leader's fuel consumption is set as a control variable in the algorithm for which its travel distance is evaluated. For that stretch trailers fuel consumption is calculated which obviously is far less than the leader. There exists a leader's percentage of fuel burn where SP is practical and aircraft switches formation role. Afterwards both aircraft equally extend range. This is discussed in greater detail in Chapter 4.

CHAPTER 4

RESULTS AND DISCUSSION

A parametric algorithm was developed in Matlab® environment based on adopted aerodynamic model and performance models to visualize aircraft's / UAV's individual and formation performance as a function of formation spacing. The algorithm comprised of a loop for incrementing lateral spacing from 0b to 2b (twice the leader's wingspan) to estimate the trailing aircraft's performance along y-axis at a fixed vertical spacing of zero. This loop helped discover best lateral spacing of 0.789b where maximum aerodynamic advantage was harvested by trailing aircraft and maximum range was extended. Similarly, a loop for vertical spacing was also incorporated to gradually increase the vertical spacing from 0b to 0.5b (half the leader's wingspan) to record aircraft performance along z-axis, at best lateral spacing. In this case maximum benefit was noted at vertical spacing of 0b, these optimum spacing points are discussed in greater detail in the subsequent sections. Furthermore, to understand fuel profiles of both aircrafts in formation, a module in the algorithm was added to feature fuel consumption as a function of formation spacing. A significant improvement in fuel consumption of trailing aircraft was discovered as compared to solo flight at optimum spacing points. This study led to a leader-switching mechanism to figure out a formation switching point where aircraft must switch their formation roles. Leader's fuel profile was considerably higher due to its lower aerodynamic efficiency as compared to the follower aircraft which was in the leader's wake / upwash at higher aerodynamic efficiency and lower fuel profile, so for a particular range to cover, the leader consumed more fuel. Leader switching-point is also discovered so that the leader while trailing at higher aerodynamic efficiency must have enough fuel so that equal extension in both aircraft range is possible.

4.1 INDIVIDUAL AIRCRAFT PERFORMANCE (JET-POWERED)

Our analysis was based on selected commercial aircrafts for their wide adaptation in aviation and availability of their aerodynamic and geometric data. Table 4.1 summarizes aircraft's required parameters necessary for this research.

Table 4.1: Aircraft Geometric Parameters

Aircraft	S	b	W_{MTOW}	W_{FUEL}	$W_{PAYLOAD}$	SFC
A380-800	845	79.80	560,000	259,465	90,720	0.52
B747-400	541.2	64.92	362,875	162,575	63,917	0.605
B737-800	125	35.79	70,535	21,000	20,240	0.63
A330-300	361.6	60.30	230,000	78,025	48,500	0.56
MD-11	338.9	51.96	273,315	117,356	52,632	0.32(SL)

Wing surface area (S) is in m^2, wingspan (b) in m and weight (W) kg. Aircrafts are designed to carry a maximum load known as maximum-take-off-weight (MTOW) beyond which it is impossible to takeoff. Fuel weight translates into fuel capacity onboard whereas payload is interpreted as luggage and passengers onboard. SFC is specific fuel consumption which describes fuel efficiency of engine design with respect to power output and its unit is pounds of fuel consumed per hour per pound-force of power. Aircraft's individual range was estimated from range the model discussed in Section 3.2.1 at an altitude of 25000ft except MD11 (sea level) and compared it with manufacture's quoted range in Table 4.2.

Table 4.2: Individual Aircraft Range

Aircraft	Estimated Range	Published Range	Percentage Error
A380-800	14,795	14,816	-0.014
B747-400	12,236	11,454	6.4
B737-800	3,541	3,685	-3.9
A330-300	10,630	10,834	-1.8
MD-11	11,834	12,632	-6.3

Range model adopted has accurately estimated aircraft range to figures quoted by manufactures. Moreover, estimated values don't overshoot from quoted figures except Boeing 747-400, that too by a margin, which provided confidence on performance model for its accurate estimation. Lift coefficient was calculated in cruise condition and drag coefficient was estimated from drag polar in Table 4.3.

Table 4.3: Aircraft Drag Polar

Aircraft	Drag Polar
Airbus A380-800	$\left(0.0133+0.0472*CL^2\right)$
Boeing 747-400	$\left(0.0130+0.0506*CL^2\right)$
Airbus A330-300	$\left(0.0142+0.0365*CL^2\right)$
Boeing 737-800	$\left(0.0187+0.0391*CL^2\right)$
MD-11	$\left(0.0165+0.0423*CL^2\right)$

4.2 PARAMETRIC STUDY OF FORMATION FLYING (JET-POWERED AIRCRAFT)

Two parameters to be investigated in formation are lateral and vertical spacing, from adopted aerodynamic model with the help of parametric algorithm to capture parametric effects on trailing aircraft performance.

Degrading effect on trailering aircraft performance was expected at zero lateral and vertical spacing as the trailing aircraft would be precisely behind the leader and in downwash region. However, as the lateral spacing increases, the trailer should come into upwash region and experience an additional lift which should result in performance gain. Similarly, an increment in vertical spacing should result in performance degradation.

4.2.1 LATERAL SPACING BENEFITS

Lateral Spacing in formation is a gap along y-axis from center of gravity (CoG) of two aircraft. In algorithm, lateral spacing y' was non-dimensionalized with respect to the leader's wing span and varied from zero to twice the wingspan. In this instance vertical spacing z' is fixed at zero so that realization of lateral spacing should be independent and a point of maximum gain can be determined along y-axis. A formation of two similar aircrafts was realized which included a formation of 2*A380, 2*B747, 2*A330,2*MD-11 and 2*B737. Leader's Lift coefficients was evaluated in cruise conditions at 25000ft except MD11 since its SFC is available for sea level at cruising speed and trailer's aerodynamic coefficient varied as a function of formation spacing evaluated from adopted aerodynamic model. Obtained coefficients were plugged into the aircraft range model so that trailer's performance can be checked as function of formation spacing. Figure 4.1 depicts range enhancement of trailer aircraft in two ship formation.

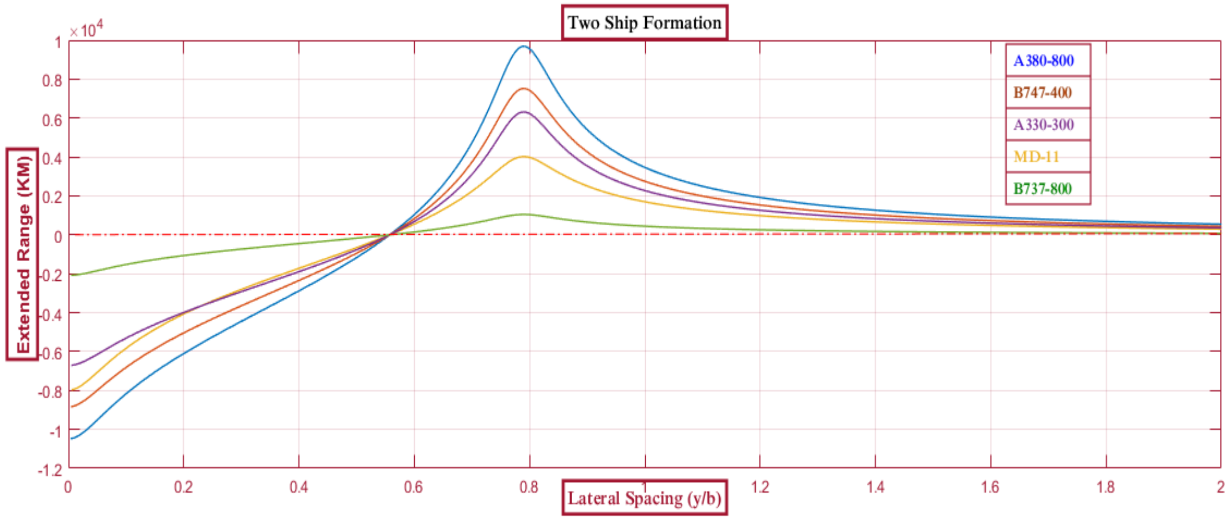

Figure 4.1: Lateral Spacing Benefits

On the figure's x-axis is the non-dimensionalized lateral spacing and y-axis is the extended range in kilometers. The dotted line in red represents zero range advantage, above this line is the range gained, meaning aircraft is flying in upwash region, whereas below the line is negative range due to downwash effects. Formation of Airbus A380-800 is discussed first which is represented by blue-colored solid-line in the figure.

At 0 lateral spacing trailing A380 was in downwash field of leader, here aircraft's drag has increased, lift has reduced so is its aerodynamic efficiency L/D and straightway negative impact on its performance (reduced range) was observed. However, as lateral spacing increased, the trailing A380 comes out of downwash at 0.55b (half the leader's wingspan), here performance in formation equaled aircraft's individual performance. Further increase in lateral spacing from 0.55b resulted in significant surge in performance due to the fact that aircraft came out of downwash and went into the upwash where it experienced an additional lift thus improving its aerodynamic efficiency, therefore, the trailer extended its range to 65% at 0.789b. This was the optimum spacing point because the maximum range was extended at this point and stretching further from 0.789b resulted in gradual decrease up to 2b where the performance benefit was almost lost. Figure 6 also includes the result of formation of two Boeing 74, Airbus A330, MD-

11 and Boeing 737, a similar trend in performance gain was observed. Table 4.4 summarizes the results at multiple lateral spacing and range extended in kilometers.

Table 4.4: Lateral Spacing Benefits

Formation	0b	0.55b	0.789b	1b	2b
A380-A380	-10,479	7	9,692	3,452	544
B747-B747	-8,834	29	7,522	2,745	437
A330-A330	-6,709	55	6,315	2,264	355
B737-B737	-2,479	5	1,045	442	76
MD11-MD11	-7,968	71	4,018	1,680	291

Formation of Boeing 747 attained percentage range enhancement of 62%, Airbus A330 to 60%, MD-11 to 34% and Boeing 737 to 31%. MD-11 and Boeing 747 have approximately similar fuel capacity and the fact that MD-11 didn't achieve similar benefits could be that its specific fuel consumption was available for sea level conditions whereas Boeing 737 is a medium sized aircraft with much less fuel onboard.

One interesting observation can be drawn from the result is that heavy aircraft got the most advantage in terms of percentage enhancement in range.

4.2.2 LATERAL SPACING BENEFITS IN HYBRID FORMATION

Hybrid is a formation of dissimilar aircrafts in which A380-800 leads some other aircraft. Since the aerodynamic model is influenced by the leader's lift coefficient CL_L, it is interesting to realize a dissimilar formation and is more suitable to commercial application as airliners choose aircraft as per their requirements. Formation constituted a leader A380-800 and trailer B747-400, A330-300, MD-11 and B737-400. Figure 4.2 represents result of hybrid formation as function of lateral spacing.

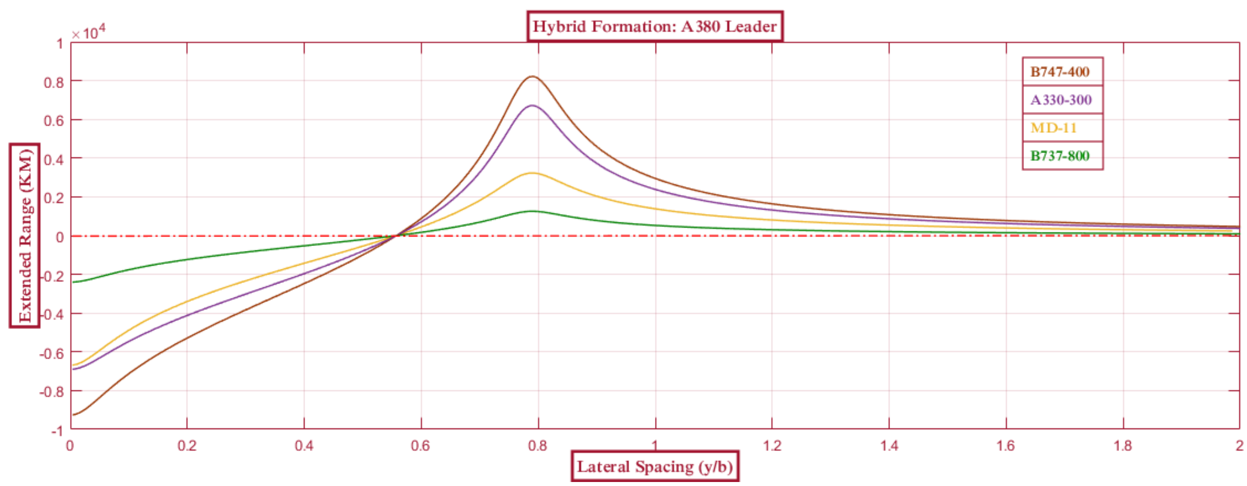

Figure 4.2: Lateral Spacing Benefits in Hybrid Formation

It is worth mentioning that in hybrid formation trailing aircraft experienced further increment in range as compared with similar formation. For example, in similar formation of two Boeing 747, trailer achieved range enhancement of 7,522 km, whereas in hybrid formation B747 achieved 8,214 km range due to the fact that a heaver aircraft (higher CL_L) lead in the latter formation. Table 5 compares range enhancement (kilometers) in similar and hybrid formation at best lateral spacing of 0.789b. It can be concluded that a heavier aircraft as leader results in further performance advantage on trailer aircraft except MD-11 because A380 at sea level would be at lower lift coefficient than MD-11.

Table 4.5: Formation Performance Comparison

Formation	B747-400	A330-300	B737-800	MD-11
Similar	7,522	6,315	1,045	4,018
Hybrid	8,214	6,716	1,255	3,229

4.2.3 VERTICAL SPACING BENEFITS

Vertical spacing in formation is the spacing between aircrafts along z-axis from CoG. Lateral spacing in this instance was fixed at 0.789b and a gradual increase in vertical spacing was introduced to estimate the performance of trailer aircraft. A formation of two Airbus A380s was investigated and Figure 4.3 illustrates the result.

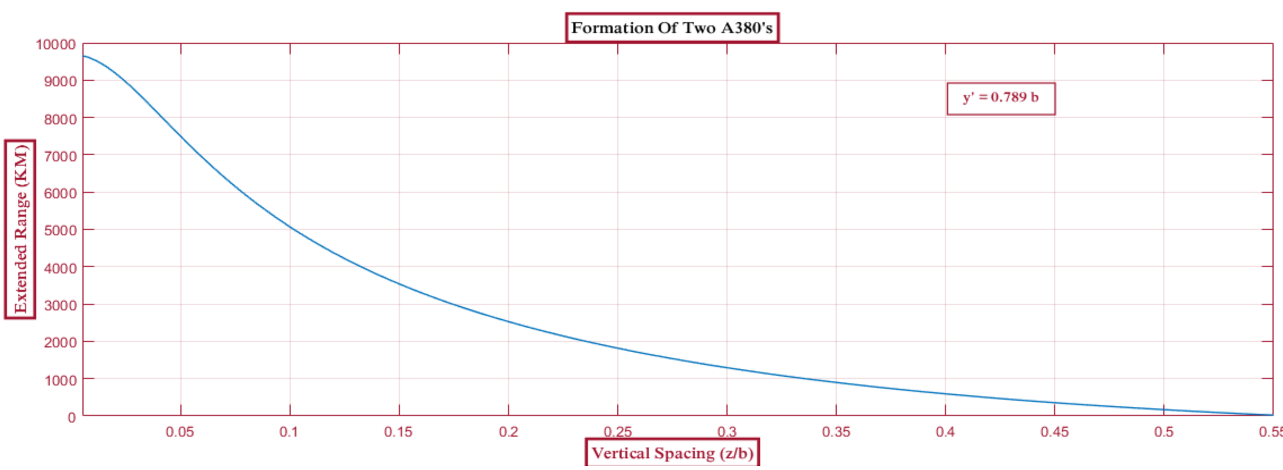

Figure 4.3: Vertical Spacing Benefits

At 0 vertical spacing the trailer's maximum range was observed, an increment in vertical spacing tended to decrease performance at 0.5b (half the leader's wingspan) i.e. its performance benefits in formation equaled individual aircraft's range. A single formation of two A380-800s was realized only because the results were not encouraging enough to further investigate vertical spacing in similar or hybrid formation.

4.3 FUEL CONSUMPTION STUDY IN FORMATION

A commercial jet burns aviation fuel for thrust to overcome drag. It has been established that the aircraft attains a higher performance in formation as compared with solo flight and since prices of jet fuel fluctuate on matters of international markets which are out of control of an air carrier therefore, a fuel consumption study is in order which investigates fuel burn benefits in similar and hybrid formation. Fuel consumption in commercial aviation is represented in terms of fuel burned per passenger per hundred kilometers and is given by:

$$Fuel\ Consumption = \left(\frac{W\_Fuel \big/ Range}{Seating\ Capacity} \right) * 100 \quad \ldots 4.1$$

Fuel consumption from the above equation is in liters consumed per passenger per 100 kilometers. Since it has been established that the range in formation is extended from aircraft's designed range therefore, fuel consumption per passenger must have reduced. This section investigates fuel saving as a function of lateral spacing.

4.3.1 FUEL SAVINGS IN FORMATION

A module of fuel saving was added into parametric algorithm derived from Eq. 4.1 and integrated into formation lateral spacing so that fuel burn can be analyzed as a function of formation spacing. A formation of similar aircrafts was studied first and results are demonstrated in Figure 4.4

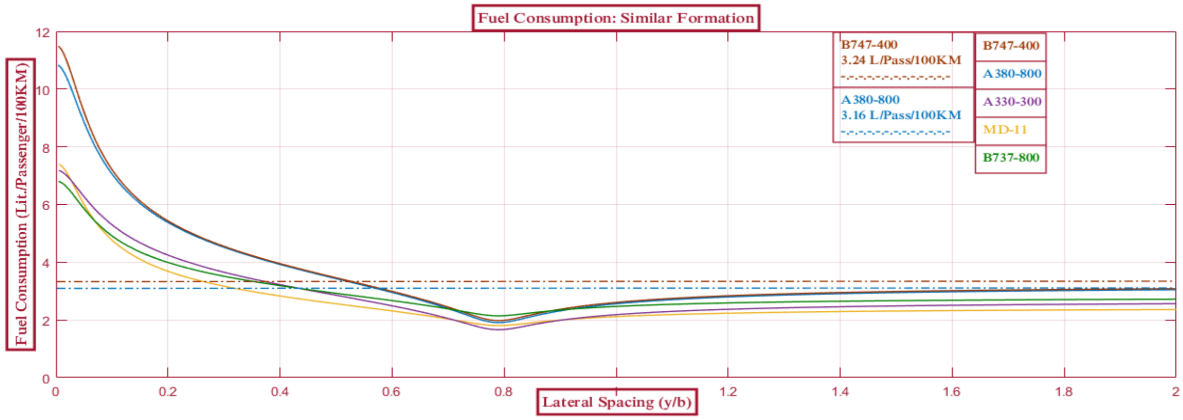

Figure 4.4: Fuel Consumption in Formation

A380 and B747 consume 3.16L & 3.24L of fuel in solo flight represented by brown and blue dotted line in Figure 9 respectively. In formation, downwash fuel consumption has significantly increased to roughly 4 times the individual consumption. However, in up-wash, it reduced to 1.90L and 1.97L for A380 and B747 respectively at a lateral spacing of 0.789b.

4.3.2 FUEL SAVINGS IN HYBRID FORMATION

It was also established that the trailer's range was further enhanced in hybrid formation hence fuel consumption study in hybrid formation of A380 as leader and, B747, A330, B737 and MD-11 as trailers was also conducted. Figure 4.5 depicts fuel consumption in hybrid formation as a function of lateral spacing with an Airbus A380-800 leading the formation.

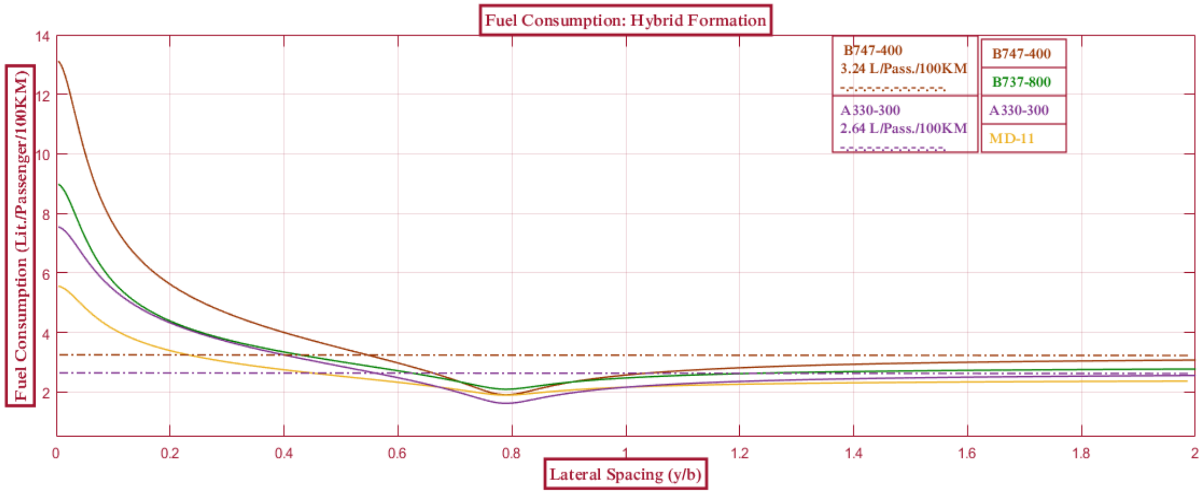

Figure 4.5: Fuel Consumption in Hybrid Formation

Table 4.6 summarizes fuel consumption in similar and hybrid formations at optimum formation spacing of $y' = 0.789b$; $z' = 0b$. Here, the values are in kilograms of fuel consumed per passenger per hundred kilometers.

Table 4.6: Fuel Saving Comparison

	A380-800	**B747-400**	**A330-300**	**B737-800**	**MD11**
Individual	3.16	3.24	2.64	2.77	2.41
Formation	1.90	1.97	1.66	2.14	1.80
Hybrid	-	1.91	1.62	2.09	1.90

Fuel consumption in a similar formation was reduced and in a hybrid formation it was reduced further. For example, a B747 consumes 3.24 L in solo flight, 1.97 L in similar formation and 1.91 L when following an A380 in hybrid formation. Similar trend of fuel saving was also observed for other aircrafts in formation.

This fuel saving benefit presents an opportunity to aviation industry to save thousands of dollars' worth of fuel annually, which makes travelling more economical and less degrading to earth's atmosphere (less CO_2 emission per kilometer).

4.4 PARAMETRIC STUDY OF FORMATION FLYING (BATTERY-POWERED UAV)

The working principle of a battery-powered UAV is significantly different than a jet powered aircraft. A battery pack provides electric power to the propulsion system of a UAV unlike a jet aircraft whose working principle (internal combustion) is far more complicated. A wide range of commercial products are available to the end user with diverse battery capacities and a battery of higher capacity results in higher endurance and range.

This thesis took different battery capacities into account i.e. 4Ah, 3Ah, 2Ah and 1Ah. This section deals with the range and endurance of a battery powered UAV whose geometry and aerodynamic parameters are given in Table 4.7.

Table 4.7: UAV Geometric Parameters

No.	Parameter	Value
1	**Mass (m)**	1.5 kg
2	**Induced drag coefficient (k)**	0.08
3	**Wing span (b)**	1.25m
4	**Area (S)**	$0.6m^2$
5	**Wing aspect ratio (AR)**	2.6
6	**Zero lift-drag coefficient (CD_o)**	0.004
7	**Area (S)**	$0.6m^2$

4.4.1 LATERAL SPACING BENEFITS (RANGE)

A parametric algorithm based on Pachter aerodynamic model and Eq. 3.5 was designed for maximum UAV range. Figure 4.6 represents the range enhancement in formation of two UAVs as a function of lateral separation when vertical spacing is fixed to zero. Dotted lines are UAV individual ranges at a particular battery capacity and solid lines represent formation range. In downwash regime, negative performance of trailing UAV was noted at all battery capacities, however, in upwash positive performance was recorded and maximum range enhancement was observed at lateral spacing of 0.789b.

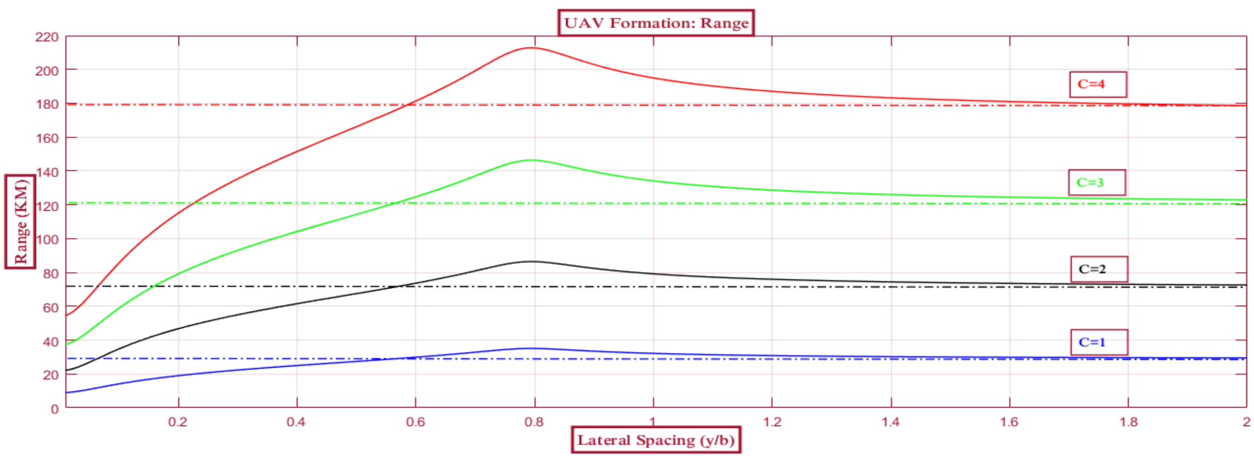

Figure 4.6: Lateral Spacing Benefits: (UAV Range)

4.4.2 LATERAL SPACING BENEFITS (ENDURANCE)

Algorithm from Eq. 3.6 and Pachter aerodynamic model for maximum endurance was designed. Results of the computation are shown in Figure 4.7 where y-axis represents endurance in hours.

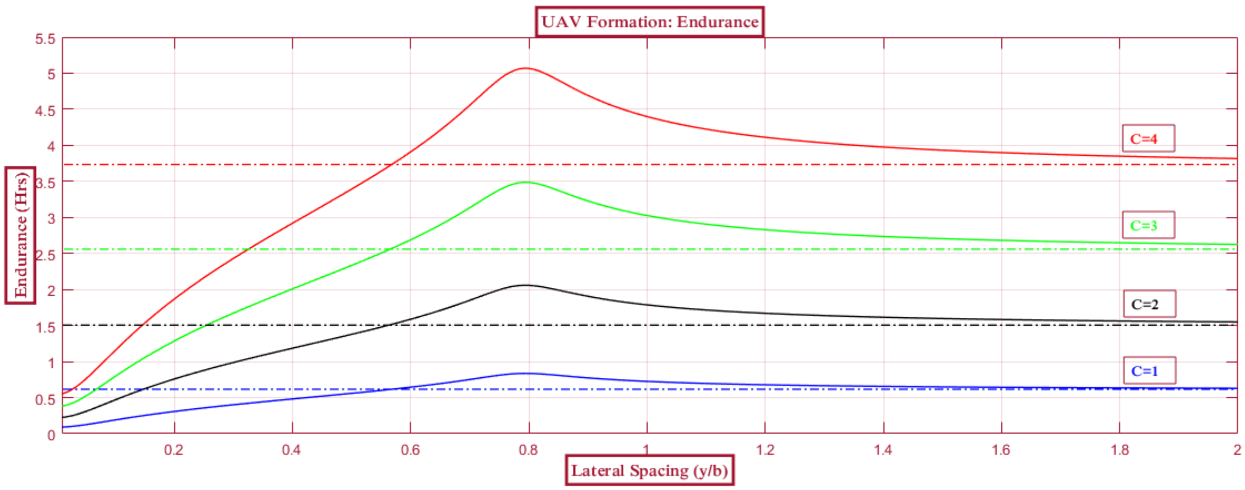

Figure 4.7: Lateral Spacing Benefits: (UAV Endurance)

Table 4.8 below summarizes performance range and endurance in kilometers and hours respectively at optimum formation spacing $y' = 0.789b,\ z' = 0$.

Table 4.8: UAV Performance Comparison

Battery	Individual Range	Individual Endurance	Formation Range	Formation Endurance
C=1	28.85	0.60	35.09	0.83
C=2	71.05	1.50	86.40	2.05
C=3	120.36	2.53	146.33	3.48
C=4	174.95	3.68	212.74	5.06

4.5 FORMATION SWITCHING

A leader switching strategy was analyzed where formation switching point was determined in terms of leader's required fuel burn in the leading role. Switching after this percentage of fuel burn should ensure equal extension in formation range from aircraft's designed range.

During pre-switching phase, the amount of fuel burned by trailer is significantly low unlike the leader for a given travel distance. Aircraft as leader covers a particular stretch at its individual L/D unlike trailer which would cover same stretch at higher L/D due to lift from upwash, thus burns less fuel. At switching point, available fuel to trailer aircraft was determined from equation below:

$$W\_fuelused = (e^{\left(R*SFC*D/V*L\right)} - 1) * (W\_payload + W\_empty + W\_reserve) \quad \text{... Eq. 4.2}$$

During post-switching, the new leader has more fuel however now it flies at lower L/D and should consume more fuel, contrary to the new trailer. It is vital to choose a switching-point where both aircrafts must have a required amount of fuel so that they equally extend range by flying at different aerodynamic efficiencies.

4.5.1 SWITCHING-POINT

Leader switching point is determined in similar and hybrid formation of two aircrafts. An algorithm was designed for evaluation of required fuel burn or travel distance by leader in lead role so that total distance traveled by leader in both roles (as leader and trailer) must equal to distance covered by trailer in both roles (as trailer and leader).

The required fuel burn and / or travel distance by leader as lead role before switching point was a control variable in the algorithm for which the trailer's fuel burn was evaluated and it turns out that fuel available to trailer was much significant as compared to the leader at switching-point. In computation it was determined that best switching-point for a formation of two A380's was when leader had burned its 55% percent fuel or had travelled 60% of its individual range. Afterwards both aircraft flew on different aerodynamic and fuel profiles, new-leader had more fuel but flew at low L/D and new-trailer had less fuel and flew at high L/D consequently, both A380s flew approximately 4,700 kilometers further from their individual ranges. Table 4.9 summarizes the result for formation of two A380s.

Table 4.9: Formation Switching Point

A380 Formation	**Pre SP**		**Post SP**	
Leader Fuel Used (L)	1,42705	**Switching Point** 55% Leader fuel burn or 60% Individual Range	New-Trailer Travel (Km)	10,610
Leader Travel (Km)	8,917		Extended Range (Km)	4,732
Trailer Fuel Used (L)	81,710		New-Leader Travel (Km)	10,633
Trailer Travel (Km)	8,917		Extended Range (Km)	4,755

During pre-switching phase of flight, the leader A380 consumed 142,705 liters of fuel to travel 8,917 km for which trailer A380 consumed only 81,710 liters of fuel. At this point, the leader must switch role with trailer A380 at optimum formation spacing points. Thereafter, new-leader had sufficient fuel onboard to travel 10,633 km as leading role where it flew at low L/D compared with new-trailer which had less fuel available and flew at high L/D for which it traveled 10,610 km in trailing role. Both A380s successfully traveled 4700 kilometers further from their designed range of 14,795 km to accumulate a total range of 19,500 km.

Similarly, a more complicated case was investigated where leader A380 and trailer B747 formed a hybrid formation unlike the previous case. It is worth mentioning that A380 has 2500 km range advantage over B747 due to aircraft design differences i.e. A380 is 35% heavier and carries 38% more fuel.

In this case formation range would not be same for both aircrafts hence switching-point was so determined where both aircraft extend equally beyond aircrafts' designed range. In first phase, the A380 led the formation while B747 harvested aerodynamic advantage till switching-point. A380 burnt 50.50% fuel to travel 8,269 km (55% of its individual range) in first phase of flight while B747 as trailer burnt 58,728 L of fuel, at this point formation switched their roles. Afterwards, B747 stretched to 7,630 km as leader and A380 to 10,175 km as trailer, B747 extended 3,663 km and A380 to 3,649 km from their respective designed ranges. A total range difference of 2500 km can be observed which is fundamentally the case with both aircraft design differences. However, the objective was to equally extend range beyond aircrafts original design and that has been achieved at selected switching point. In both similar and hybrid formation, initially trailing aircraft achieved a few tens kilometers extra range comparatively which may be utilized for maneuverability required to switch roles. Table 4.10 summarizes computational results.

Table 4.10: Hybrid Formation Switching Point

Hybrid Formation	**Pre SP**		**Post SP**	
A380 Fuel Used	1,31030	**Switching Point**	A380 Travel	10,175
A380 Travel	8,269	50.5% Leader (A380)	Extended Range	3,649
B747 Fuel Used	58,728	fuel burn or 55%	B747 Travel	7,630
B747 Travel	8,269	Individual Range	B747 Ext. Range	3,663

4.6 CHALLENGES IN FORMATION FLYING

Commercial application of formation flying is never realized because wake vortices are considered a safety hazard. Incidents were recorded where aircraft came close to the wake of other aircraft for which loss of vital controls were reported. One such incident involved an Airbus A300 (American Airlines Flight 587) which was cleared for takeoff 1 min 20 sec after a Japan Airlines Boeing 747-400 took off. Flight 587 hit turbulent air soon after takeoff and lost control which were never recovered despite the efforts from pilots killing 265 (all 260 on board; 5 on the ground) [18]. Therefore, authorities forcefully implement minimum spacing regulations which include longitudinal spacing regulation as a function of aircraft category [19] (6NM spacing for Cessna class aircraft for wake originated from Airbus A380-800) and vertical spacing (thousand feet) as standard. In light of the mentioned events and forced regulation, formation flying in commercial aviation/aeronautics is not possible as of now. However, upon closer analysis of incidents it was figured out that wake originating from dynamic phases of flight i.e. take-off, climbing, descend and landing is much riskier than in cruise. Moreover, experimental studies of formation as mentioned in literature review were successfully conducted and significant benefits were reported.

4.7 FUTURE OF AIR TRANSPORTATION

In recent years, the number of passengers travelling through air has significantly grown and is expected to grow in coming years as well. To meet demands, in December 2004 Joint Planning and Development Office (JPDO) laid plans for the Next Generation Air Transportation System [20] with emphasis on the need for a new technology-enabled approach to air transportation and through these plans, the intended air capacity is to increase 3 times the current capacity triggering space management challenge. In current technology it is the Air traffic control's responsibility to maintain a safe spacing among aircrafts midair. However, in order to meet new requirements, set by Federal Aviation Authority new models designed by researcher's delegate authority of inter-aircraft spacing to onboard pilots. If this model qualifies for implementation and practical use, this thesis could possibly see a wide adoption within airliners.

CHAPTER 5

CONCLUSIONS & FUTURE WORK

In conclusion, natured inspired formation flying presented a good omen for our problem statement and it resulted in tremendous benefits.

- Similar and hybrid formation of commercial aeronautics was realized to estimate the performance.
    - In similar formation a wide body aircraft travels up to 65% further in formation as compared to individual range and medium sized aircraft in formation can travel 31% further for same given amount of fuel.
    - In hybrid formation, trailer aircraft travel 10% even further with a heavier aircraft leading. A dissimilar formation is a practical option made available which presents unique perspectives to aviation/airliners and provides even greater benefits.
    - Ever fluctuating fuel prices is a major concern for airliners and in this thesis fuel saving benefits are also addressed. Most importantly, formation as a whole burn less fuel for a given range and therefore less CO_2 emission makes travel less deteriorating for the environment.

- Onboard constraints of power on a small UAV are addressed with increased range and flight duration.
    - Range at different battery capacities was increased up to 22 percent and endurance up to 37 percent.

A future prospect may include a point-mass simulation model of formation flight where instantaneous aerodynamic efficiency and fuel weight variation can be realized for better and more accurate determination of formation switching-point. Proposed model may also incorporate maneuverability requirements for switching formation role at switching-point.

APPENDIX

SIMILAR FORMATION (AIRBUS A380): LATERAL SPACING CODE

```
V = 542.41;        % cruising velocity in knots.
v = 915.4;         % cruising velocity in ft/s.
p = 0.001019;      % air density at 25000 feet in slugs.
S = 9095.5;        % surface area in feet squared.
b = 261.81;        % wingspan in feet.
AspR = 7.53;       % aspect ratio.


Fuel_Weight = 572022.409;      % fuel weight in pounds.
Payload_Weight = 200003.36;    % payload weight in pounds.
Empty_Weight = 820119.615;     % empty weight in pounds.
Reserve_Weight = 28601.12;     % reserve weight in pounds.
SFC = 0.52;                    % specific fuel consumption.
l = 1234588.67;                % aircraft's lift in cruise.
q = 0.5*p*v^2;                 % dynamic pressure in cruise.
Cl = l/(q*S);                  % lift coefficient.
Cd = 0.0133+(0.0472*Cl^2);     % A380 drag polar.
d = Cd*q*S;                    % drag coefficient.


meu = 0.0501;      % vortex core radius, non-dimensionalized w.r.t wingspan.
LS = 6.94;         % lift-curve slope.
t = 524;           % variables to record measurements.
yp = zeros (1, t);
LbyD = zeros (1, t);
Range_A380_Formation = zeros (1, t);
Extd_Range_A380 = zeros (1, t);
Fuel_Burned_Formation_A380 = zeros (1, t);


Range_A380 =
(V/SFC)*(l/d)*(log(1+((Fuel_Weight)/(Empty_Weight+Payload_Weight+Reserve_Weig
ht))));
                                            % individual range in NM.
R_KM = round(Range_A380*1.852);             % individual range in kilometers.
Fuel_Burned = ((259465/R_KM)/555) *100;     % fuel consumption per passenger.

for ybar = 1:t                 % lateral spacing variation.

    yp(ybar) = ybar/b;         % code for Pachter aerodynamic model.

    Q = log ((yp(ybar)^2+meu^2)/((yp(ybar)-0.785) ^2+meu^2)) - log
(((yp(ybar)+0.785) ^2+meu^2)/(yp(ybar)^2+meu^2));

    DeltaCL = (LS/(3.14*AspR)) *Cl*(2/ (3.14^2)) *(Q);
    CL = Cl+DeltaCL;
    L = CL*q*S;
```

```
    DeltaCD = (1/(3.14*AspR)) *(Cl)*(CL)*(2/ (3.14^2)) *(Q);
    CD = Cd-DeltaCD;
    D = CD*q*S;

    LbyD(ybar) = L/D;

    RangeofA380Formation = (V/SFC) * (L/D) * (log (1 +
((Fuel_Weight)/(Empty_Weight+Payload_Weight+Reserve_Weight))));

    Range_A380_Formation(ybar) = round (RangeofA380Formation*1.852);

    Extd_Range_A380(ybar) = (Range_A380_Formation(ybar)-R_KM);

    Fuel_Burned_Formation_A380(ybar) =
((259465/Range_A380_Formation(ybar))/555) *100;

fprintf ('Lateral Spacing = %f | Range = %f | Formation Range = %f |
Extended_Range = f\n', yp(ybar), R_KM, Range_A380_Formation(ybar),
Extd_Range_A380(ybar))

end

hold all
plot (yp, Fuel_Burned_Formation_A380)
```

HYBRID FORMATION (Leader A380, Trailer B747): LATERAL SPACING CODE

```
V=562.25;          % cruising velocity of B747 in knots.
v = 948.98;        % cruising velocity of B747 in ft/s.
p = 0.001019;      % air density at 25000 feet in slugs.
S = 5825.4283;     % surface area of B747 in feet squared.
b = 261.81;        % wingspan of A380 in feet.


Fuel_Weight = 358416.523;     % fuel weight of B747 in pounds.
Payload_Weight = 140912.86;   % payload weight of B747 in pounds.
Empty_Weight = 534995.772;    % empty weight of B747 in pounds.
Reserve_Weight = 17920.826;   % reserve weight of B747 in pounds.
SFC = 0.605;                  % specific fuel consumption of B747.
l = 800002.434;               % B747's lift in cruise.
q = 0.5*p*v^2;                % B747's dynamic pressure.
CDW = 0.0130+(0.0506*CLW^2);  % B747's dragpolar.
d = CDW*q*S;                  % B747's drag coefficient.
CLW = l/(q*S);                % B747's lift coefficient.
AspR = 7.7;                   % B747's aspect ratio.
CLL = 0.3179;                 % A380's lift coefficient in cruise.


LS = 7.37;         % B747's lift curve slope.
meu = 0.0501;      % vortex core radius, non-dimensionalized
t = 524;           % variables to record measurements.
ybar = 1;
yp = zeros (1, t);
LbyD = zeros (1, t);
Range_B747_Hybrid_Formation = zeros (1, t);
Extd_Range_Hybrid = zeros (1, t);
Fuel_Burned_Formation_Hybrid = zeros (1, t);


Range_B747_Hybrid = (V/SFC) * (l/d) * (log (1 +
((Fuel_Weight)/(Empty_Weight+Payload_Weight+Reserve_Weight))));
                                    % B747's individual range in NM.
R = round(Range_B747_Hybrid*1.852); % B747's individual range in kilometers.

for ybar =1:t                       % lateral spacing variation.

    yp(ybar) = ybar/b;              % code for Pachter aerodynamic model.

    Q = log ((yp(ybar)^2+meu^2)/((yp(ybar)-0.785) ^2+meu^2)) - log
(((yp(ybar)+0.785) ^2+meu^2)/(yp(ybar)^2+meu^2));

    DeltaCL = (LS/(3.14*AspR)) *CLL*(2/ (3.14^2)) *(Q);
    CL = CLW + DeltaCL;
    L = CL*q*S;

    DeltaCD = (1/(3.14*AspR)) *(CLL)*(CL)*(2/ (3.14^2)) *(Q);
    CD = CDW-DeltaCD;
```

```
    D = CD*q*S;

    LbyD(ybar) = L/D;

    RangeofB747Formation = (V/SFC) * (L/D) * (log (1 +
((Fuel_Weight)/(Empty_Weight+Payload_Weight+Reserve_Weight))));

    Range_B747_Hybrid_Formation(ybar) = round (RangeofB747Formation*1.852);

    Extd_Range_Hybrid(ybar) = (Range_B747_Hybrid_Formation(ybar)-R);

    Fuel_Burned_Formation_Hybrid(ybar) =
((162575/Range_B747_Hybrid_Formation(ybar))/416) *100;

fprintf ('Lateral Spacing = %f | Range = %f\n', yp(ybar),
Fuel_Burned_Formation_Hybrid(ybar))
end

hold all
plot (yp, Fuel_Burned_Formation_Hybrid)
```

SIMILAR FORMATION (AIRBUS A380): VERTICAL SPACING CODE

```
V = 542.41;
p = 0.001019;
v = 915.4;
S = 9095.5;
b = 261.81;
AspR = 7.53;


Fuel_Weight = 572022.409;
Payload_Weight = 200003.36;
Empty_Weight = 820119.615;
Reserve_Weight = 28601.1;
SFC = 0.52;
l = 1234588.67;
q = 0.5*p*v^2;
Cl = l/(q*S);
Cd = 0.0133+(0.0472*Cl^2);
d = Cd*q*S;
LS = 6.94;
meu = 0.0501;


zbar = 1;
yp = 0.789;
t = 146;
zp = zeros (1, t);
Range_A380_Formation = zeros (1, t);
Extd_Range_A380 = zeros (1, t);


Range_A380 = (V/SFC) * (l/d) * (log (1 +
((Fuel_Weight)/(Empty_Weight+Payload_Weight+Reserve_Weight))));

R_KM = round(Range_A380*1.852);


for zbar = 1:t              % vertical spacing variation.

    zp(zbar) = zbar/b;

    Q = log ((yp^2+zp(zbar)^2+meu^2)/((yp-0.785) ^2+zp(zbar)^2+meu^2)) - log
(((yp+0.785) ^2+zp(zbar)^2+meu^2)/(yp^2+zp(zbar)^2+meu^2));

    DeltaCL = (LS/(3.14*AspR)) *Cl*(2/ (3.14^2)) *(Q);
    CL = Cl+DeltaCL;
    L = CL*q*S;

    DeltaCD = (1/(3.14*AspR)) *(Cl)*(CL)*(2/ (3.14^2)) *(Q);
    CD = Cd-DeltaCD;
    D = CD*q*S;
```

```
    RangeofA380Formation = (V/SFC) * (L/D) * (log (1 +
((Fuel_Weight)/(Empty_Weight+Payload_Weight+Reserve_Weight))));

    Range_A380_Formation(zbar) = round (RangeofA380Formation*1.852);

    Extd_Range_A380(zbar) = (Range_A380_Formation(zbar)-R_KM);

fprintf ('Vertical Spacing = %f | Range = %f | Formation Range = %f |
Extended Range = %f\n', zp(zbar), R_KM, Range_A380_Formation(zbar),
Extd_Range_A380(zbar))

end
plot (zp, Extd_Range_A380)
```

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