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DEVELOPMENT OF LIFTING LINE THEORY FOR THE FANWING PROPULSION SYSTEM

by

CHRISTOPHER KAMINSKI

A thesis submitted in partial fulfillment of the requirements
for the Honors in Major Program in Aerospace Engineering
in the College of Engineering and Computer Science
and in the Burnett Honors College
at the University of Central Florida
Orlando, Florida

Spring 2021

Thesis Chair: Dr. Michael Kinzel

ABSTRACT

The FanWing propulsion system is a novel propulsion system which aerodynamically behaves as a hybrid between a helicopter and a fixed wing aircraft, and if the knowledge base with regards to this novel concept can be fully explored, there could be a new class of aircraft developed. In the current research, only 2D CFD studies have been done for the FanWing, hence the 3D lift characteristics of the FanWing have been unknown thus far, at least in the theoretical domain. Therefore, it was proposed to develop a modified Prandtl's Lifting Line Theory numerical solution and a CFD solution, comparing the results of each. A new variable was introduced into the classical Lifting Line Theory solution, $\alpha_{i,FW}$, to account for the additional lift produced by the FanWing as opposed to a traditional airfoil. This variable, $\alpha_{i,FW}$, is a function of the wing angle and the velocities taken at three-quarter chord length on the FanWing. The introduction of this variable was informed by other papers which superimposed velocities when developing Lifting Line Theory for unconventional airfoil planforms. After introducing a correction factor, the numerical model aligned with the 3D CFD results where LLT assumptions were valid. For the 3D simulation, it was observed that the lift per unit span rapidly increases from quarter span to wingtip, which is different from traditional wing planforms. This study provides a valuable first step towards documenting the 3D lift characteristics of the novel FanWing propulsion system.

ACKNOWLEDGEMENT

I would like to thank Dr. Kinzel for the numerous hours that he has put into advising me and introducing me to the helpful tool that is Computational Fluid Dynamics. His assistance has greatly expanded by knowledge of fluid dynamics and developed a love for research that I hope to continue with in my career as an engineer. His assistance allowed me to go from being a normal student, to having a vast knowledge of understanding pertaining to fluid dynamics research. I would like to thank Dr. Bhattacharya for putting in the time and effort for me by being a part of my committee. I would like to thank my wife for being my co-laborer in my academic career by understanding the difficulties of the rigorous schedule I have had to maintain throughout my academic career. I would also like to thank Patrick Peebles for coming up with the FanWing concept, and for the knowledge that he published with regards to this novel propulsion system.

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LIST OF ABBREVIATIONS, ACRONYMS, AND NOMENCLATURE

2D – Two-Dimensional

3D – Three-Dimensional

α – Angle of Attack

α_i – Induced Angle of Attack

$\alpha_{i,FW}$ – Angle of Attack Induced by FanWing

b – Span Length

c – Chord Length

CFD – Computational Fluid Dynamics

dS – Iterative Span Length

Γ – Circulation

L – Lift

LLT - Lifting Line Theory

m/s – meters per second

RF – Relaxation Factor

ρ – Density

TAT – Thin Airfoil Theory

V_{tot} – Total Magnitude of Velocity at Three-Quarter Chord on the FanWing

$V_{FW,x}$ – FanWing Induced Velocity in the x-direction

$V_{FW,y}$ – FanWing Induced Velocity in the y-direction

V_∞ - Free Stream Velocity

CHAPTER ONE: INTRODUCTION

The FanWing is a novel distributed propulsion concept which gives a fixed-winged craft the STOL, autorotation, and heavy-lifting abilities which would normally be associated with a helicopter, thus combining the inherent advantages of both systems. The FanWing operates in a similar manner to other distributed propulsion systems that have recently been developed. The FanWing creates lift as a fixed-wing aircraft would, yet this is done independently of airspeed, thus giving the FanWing various STOL capabilities which would not normally be achievable for a fixed-wing aircraft. This propulsion concept's potential is promising when considering not only the capabilities of the aircraft, but also the efficiency. In a report produced for the 28th International Congress of the Aeronautical Sciences, an exploratory study declared, "A conceptual and costed comparison of four different aircraft and rotorcraft configurations has shown that, with these developments, the FanWing concept could now offer an interesting and unique capability, with short-field performance close to that of helicopters and tiltrotor aircraft, but with operating economies close to that of conventional aircraft." [1] It is estimated by FanWing Ltd., a company in the UK researching the propulsion system for viability, that the FanWing could achieve the double the range of a helicopter on the same amount of fuel. In addition, in the scenario of engine failure, the FanWing can safely approach the ground through achieving a glide ratio of roughly 3:1, making the FanWing safer than a helicopter in the event of double engine failure. The STOL ability of the FanWing also means that the possible angles of attack are much greater than that of a traditional aircraft, along with an extremely low stall speed. [2] While all of these estimates are merely speculation, such metrics are in accordance with other distributed propulsion systems in development.

Figure 1: This UAV FanWing Prototype was built in 2010 and flew in the Farnborough Airshow as a technological demonstrator. [1]

The FanWing propulsion system has a myriad of possible commercial applications such as cargo transport, UAVs, and ultralight aircraft for personal or industrial use. Given the STOL capabilities, it is ideally suited for recreational use or industrial heavy-lifting applications. Despite the potential advantages, the FanWing design has never been developed past rudimentary prototypes, making the concept is worthy of further exploration and development. If enough interest and capital were directed towards developing the FanWing further, it is highly likely that a new class of aircraft could be produced which would introduce capabilities unseen in either fixed-wing aircraft or rotorcraft.

The latest iteration of the FanWing aircraft concept was the EU SOAR project which was a joint collaboration comprised of researchers from FanWing Ltd., Saarland University, and the Von-Karman Institute. [3] The study ran from 2013 to 2015 and had a favorable reporting of results. According to the report, “The FanWing was shown to have scenarios with lower operating costs than its competitors in both the 500kg-2500kg payload class and the 10000kg payload class…In a generic market, the Fan Wing needs one of two things to be economically successful: the market must pay a premium for low-speed maneuvering missions and/or the low takeoff distance must enable an owner-pilot model in the same market with the owners having a high utilization rate." [3] Unfortunately, however, this is the last time the FanWing has been explored commercially. To generate future commercial and academic interest, successive iterations of the FanWing propulsion system must be made, as well as further development of theory that governs such a unique propulsion system. Therefore, the following study seeks to characterize the lift generation of the FanWing using a development of Prandtl's Lifting Line Theory, so that the understanding of this unique propulsion system will have a theoretical foundation upon which to iterate the designs further. Such theoretical development will be contrasted with the lift distribution findings of a Computational Fluid Dynamics simulation to demonstrate the validity of the theoretical findings.

Prandtl's Classical Lifting Line Theorem uses the Kutta-Joukowski Theorem which describes the relationship between lift and circulation, expressed as Γ, to describe the relationship between vortex distribution along a wingspan and lift distribution per unit span of wing. The Kutta-Joukowski law is derived from a two-dimensional potential flow solution, and Prandtl's theory extends such findings along a three-dimensional wing. To extend the theory to three dimensions, Prandtl's Lifting Line theory required s local section of lift to be equal to the cross product of the local fluid velocity vector with the local circulation vector, which is then multiplied by the fluid density. From the equation, $\rho(V \times \Gamma)$, a lift per unit span of the wing is able to be obtained which is parallel to the vorticity strength. [4] The two primary equations of Lifting Line Theory are shown below, with Equation 1 giving the lift per unit span, and Equation 2 giving the relationship between lift coefficient and circulation. [5]

$$\frac{dL(y)}{dy} = \rho V_{\infty} \Gamma(y) \quad (1)$$

$$\Gamma(y) = \frac{1}{2} c(y) C_l(y) V_{\infty} \quad (2)$$

The equations given will be modified to characterize the vorticity of the FanWing's wake, and the corresponding lift distribution. Through modifications to Prandtl's theory, an understanding of the lift characteristics of a baseline FanWing can be established, thus giving a greater understanding of the FanWing's unique form of lift generation. By establishing a theoretical basis for the method of lift generation from a three-dimensional FanWing, this novel concept can be understood in a greater capacity, and subsequently developed upon.

CHAPTER TWO: METHODOLOGY

Explanation of Methodology

Two primary methods are used to obtain the lift distribution along a FanWing, a theoretical development of Lifting Line Theory, and a Computational Fluid Dynamics simulation on Star-CCM+ commercial CFD code developed by CD-Adapco and Siemens [6]. The computational fluid dynamics simulations and optimizations was conducted at the CFAL Laboratory at the University of Central Florida. The purpose of developing a CFD simulation to characterize lift distribution over a FanWing is to confirm the validity of the theoretical development of Lifting Line Theory. The results given are to be compared, and an alignment of results between LLT and CFD will give indication that the experimental and theoretical results are valid. Two methods will be used to develop the characteristics of lift for a FanWing. The first will be to develop a numerical Lifting Line Theorem which will be used to describe the FanWing propulsion system's lift characteristics. Such a solution will give lift per unit span, L' and Γ(y), which will be input with variables from the CFD solution, with a comparison of results to follow.

CFD Methodology: Geometry

In developing a CFD simulation for the FanWing, there are a variety of previous papers to reference which can inform a proper development of the simulation. To establish a standardized lift per unit span for the FanWing which can then be used to inform the theoretical solution, the CFD simulation will follow previous FanWing CFD simulation parameters, including regarding the geometry of the FanWing planform. It is chosen that the geometry of the FanWing in this CFD simulation will be based upon the paper by Du Siliang and Tang Zhengfei [7], given its' geometric similarity to the majority of the physical prototypes produced for FanWing research. The geometry is shown in Figure 2 below. The geometric parameters are set according to the Figure 2. The opening angle, denoted by Ψ, is set to 24°. The span length of the wing is set to 20 meters, and the chord length is set to 3.74 m from leading edge to the trailing edge, defined by Figure 2. The radius of the fan is set to 1 m. The trailing edge angle, defined by θ, is set to 29.1°, similar to other FanWing configurations. The total span of the FanWing in the CFD simulation is set to 20 meters, due to Prandtl's LLT necessitating a high-aspect ratio wing for accurate lift distribution prediction. [5] While many studies have been done with regards to airfoil selection for the FanWing rotors, an asymmetric NACA 6510 airfoil was used for similarity with cambered airfoils used in previous studies.

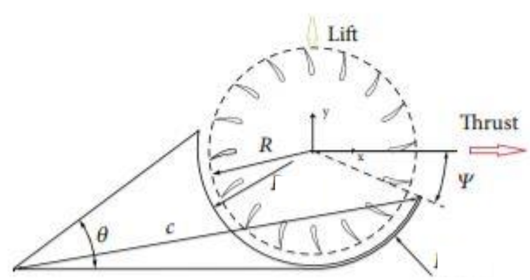


Figure 2: Geometric and force definitions of FanWing used for CFD simulation.[7]

CFD Methodology: Meshing

Due to the necessity of modeling the rotational region for the FanWing, two regions were formed for the CFD simulation, a domain region, and a rotation region. Similar to other FanWing studies, a polyhedral mesh was selected for the rotational region, whereas a hexahedral mesh was chosen for the domain. [8] The purpose of the polyhedral meshing in the rotational region is to capture the complex turbulent flows within the region. The polyhedral mesh is optimal for the curvature of the airfoil shapes within the rotational region as well. To accurately capture the complex flow around the airfoils within the FanWing rotor, a Prism Layer Mesher with 10 layers is added to the mesh. For the rotational region mesh, a base size of .075 m is used, where the target surface size is 50% of this value, in order to sufficiently capture the complex flow. In total, the rotational region has 11,183,496 cells. The hexahedral mesh in the domain is chosen for computational efficiency where it is not necessary to have such a fine mesh to pick up the flow characteristics in this region. The base size and target surface size remain the same; however, the hexahedral mesh creates far fewer cells within the domain region, with a total of 1,513,114 cells. The resulting mesh is shown in Figure 3 below.

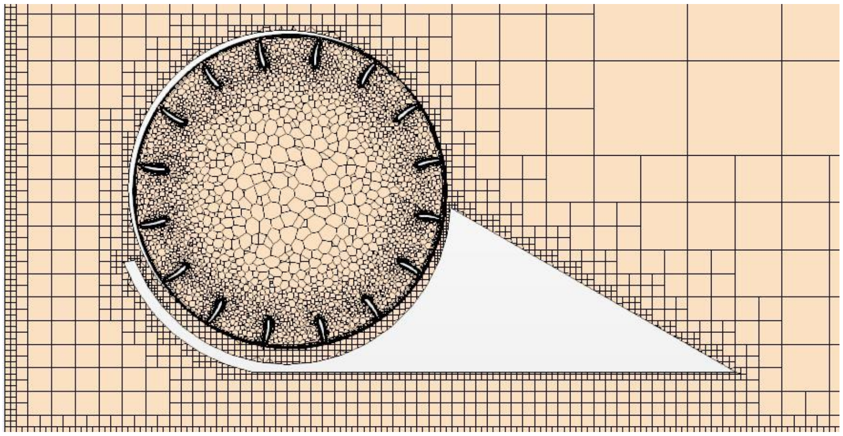


Figure 3: The figure displays the resulting mesh for the FanWing within the CFD simulation.

CFD Methodology: Physics

The CFD physics models selected also comes from other studies involving CFD investigation of flow over a FanWing. [9] The fluid medium selected within Star CCM+ is an ideal gas. The inlet velocity over the FanWing is set to 6 m/s, with the boundaries of the Domain around the FanWing being free stream walls set to an equivalent velocity. The timestep for the Unsteady Flow solver is set to .001 seconds, and the FanWing rotates at 1400 m/s. This gives an 8.4° rotation per time step, and multiple iterations of the simulation were done to minimize the difference in recorded lift value between each time step. It is proper to include a timestep sufficient to capture 1/20th of a rotation, therefore this timestep is deemed acceptable. For the turbulence model, the Kappa-Epsilon Turbulence Model was selected, sufficient for modeling the flow behavior of the FanWing. [10] A Reynolds Averaged Navier-Stokes's solver is included with these models.

Numerical Methodology

The numerical solution for the FanWing is a modification of a numerical solution for Prandtl's Classical Lifting Line Theory for an elliptical wing. The numerical solution was developed using Octave, a free, high-level programming language similar to MATLAB. In developing the Octave code, several steps were taken to numerically solve for Γ distribution and lift distribution. The initial portion of the code is dedicated to discretizing a rectangular wing into panels. [4] This is done through an iterative for loop which divides the wing into *n* panels, where the total span length is defined as *b*, with *dS* being the span length of the wing divided by *n* panels. Each panel is indexed by the iterative loop from *ii…n*. The indexing for each span along the wing is shown in Equation 3. Through this initial iterative loop, the span center, defined as y_c, is also indexed for each panel, as shown in Equation 4.

$$y_{ii} = \frac{-b}{2} + (ii - 1)dS \tag{3}$$

$$y_{c_{ii}} = \frac{-b}{2} + (ii - 0.5)dS \tag{4}$$

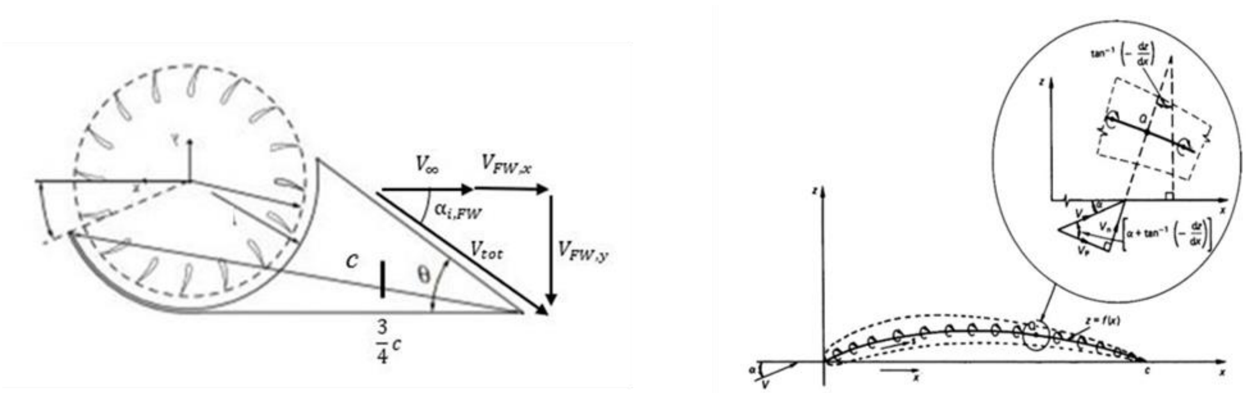
In the same iterative loop, an initial Γ distribution is obtained, in order to numerically obtain induced angle of attack, α_i. The equation used to obtain the initial Γ distribution across the wing is listed in Equation 6, with Γ_0 being defined by Equation 5, which is the standard Γ_0 equation according to Prandtl's Lifting Line Theory. Here, $C_{l\alpha}$ is defined as 2π radians, according to Thin Airfoil Theory for a symmetric airfoil. [5] In a subsequent for loop, induced angle of attack is obtained via a numerical integration shown by Equation 7 which utilizes the Γ distribution and the trapezoidal rule.

$$\Gamma_0 = \frac{1}{2} V_\infty c (C_{l\alpha} \alpha) \tag{5}$$

$$\Gamma_{ii} = \Gamma_0 \sqrt{1 - \left(\frac{2y_{c_{ii}}}{b}\right)^2} \tag{6}$$

$$\alpha_{i_{ii}} = \frac{1}{4\pi V_\infty} \left(\alpha_{i_{ii}} + \frac{1}{2} dS \left(\frac{\frac{d\Gamma}{dS}_{ii}}{y_{c_{ii}} - y_{ii}} \right) + \frac{\left(\frac{d\Gamma}{dS}\right)_{ii+1}}{y_{c_{ii}} - y_{ii+1}} \right) \tag{7}$$

To obtain the final Γ distribution, and, subsequently, the L' values, for a FanWing propulsion system, new parameters will be introduced which will modify the conventional numerical solution to Prandtl's Lifting Line Theory. The model will account for the additional lift produced by the FanWing propulsion system using velocity vectors measured from the three-quarter chord, to introduce an induced α which accounts for the increase in lift produced by the FanWing over a traditional wing. The proposed model for accounting for the increase in lift generated by the FanWing propulsion system is a derivation of Weissinger's Approximation for Thin Airfoil Theory. In Weissinger's Approximation [11], the increase in vorticity and lift is proportional to α minus the slope of the camber line at three-quarters chord length. The assumption is made that the FanWing enforces a flow tangency to the three-quarter chord in a similar fashion to produce an increase in lift in the same manner that an increase in the slope of a camber line produces lift for an asymmetric airfoil. Figure 4 below illustrates the approximation made by this model.



A) B)

Figure 4: Figure 4A [7] illustrates the FanWing induced alpha approximation in the numerical solution, which is correlated with TAT and Weissinger's Approximation in Figure 4B [12].

The method of superposition illustrated here has been exercised by various other applications when determining lift distribution. In a paper by Balu, the equations for superposition of velocities are applied to horizontal axis wind turbines. [13] In the same manner, the induced velocity is superimposed on the three-quarter chord of the FanWing in order to produce an additional induced alpha. Equation 8 shows the method of superposition used by Balu and others [14], which accounts for the increase in lift distribution across a wing as a result of an induced velocity, *u(y)*. Similarly, the two-dimensional lift coefficients due to twist, camber, and flap are all added together to produce a total two-dimensional coefficient of lift, which varies across the span of the airfoil.

$$L'(y) = \rho\big(V_\infty + u(y)\big)\Gamma(y) \tag{8}$$

$$C_l = 2\pi\left(\alpha - \frac{dz}{dx}\right) \quad (9)$$

$$C_l = 2\pi\left(\alpha + \alpha_{i,FW}\right) \quad (10)$$

For the FanWing, because the model is approximating the FanWing in a similar manner to Thin Airfoil Theory, the model superimposes an induced alpha as opposed to the velocity, due to the velocity not accounting for the positive lift produced by the FanWing at a zero angle of attack. This induced alpha value acts as a substitute for the slope of the camber line which TAT and Weissinger's approximation accounts for at three quarter chord, as shown in Equation 9. This methodological approach is similar to a paper by Pate et al., where the effective angle of attack is a function of the shape of the wing planform. [15] The model developed for the FanWing accounts for the increase in lift produced by the rotor through $\alpha_{i, FW}$. In the numerical model, the FanWing induced alpha will be accounted for in the final Γ distribution calculation in the numerical solution. Equation 10 gives the lift coefficient calculated in this manner for the numerical model of the FanWing lift distribution. This new coefficient of lift is integrated into the new Γ_{ii} iterative loop. This updated Γ_{ii} will be used to predict lift distribution, accounting for the increase in lift produced by the FanWing propulsion system. This would make the lift distribution of the FanWing a function of the original parameters of Prandtl's Lifting Line Theory, while accounting for the additional lift produced by the FanWing. Figure 5 below shows the vector addition used to obtain $\alpha_{i,FW}$ which is used for the numerical model.

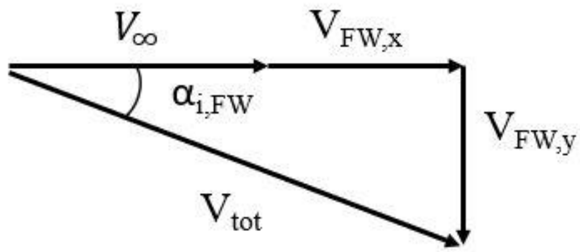


***Figure 5**: The vector addition used to obtain αi,FW, which is used to account for the increase in lift produced by the FanWing Propulsion system on the wing. This superposition method of obtaining lift is applied for the FanWing from other applications.*

The vector addition shown above is then added into the numerical solution to obtain total angle of attack, denoted as α_{tot}, which is then utilized in the numerical solution in order to obtain Γ_{ii}, as given in Equation 11 below. Here, RF is representative of a relaxation factor that is used to help the numerical solution obtain convergence. The final calculation of lift distribution for the numerical model is given by Equation 12, after taking into account the updated Γ distribution.

$$\Gamma_{ii} = \Gamma_{ii} + RF(\frac{1}{2}V_{x,tot}c\big(C_{l\alpha}(\alpha_{tot} - \alpha_{i_{ii}})\big) - \Gamma_{ii}) \tag{11}$$

$$L' = \rho\Gamma_{ii}V_{x,tot} \tag{12}$$

CHAPTER THREE: RESULTS

CFD Results

The FanWing CFD result was run for about 72 hours utilizing the CPU at the CFAL Laboratory. Utilizing the time step of .001s, the simulation was run until .27 seconds, enough to achieve a steady state oscillation of lift values. The scalar scene is shown in Figure 6 below. The scene displays the velocity scalar values at mid-span. From this scene, it can be observed how the FanWing forces flow down the wing planform, thus generating lift and thrust. The scene corresponds with other scalar scenes for 2D FanWings, confirming the result achieved. The inlet velocity of 6 m/s accelerates to roughly 85 m/s at the three-quarter chord.

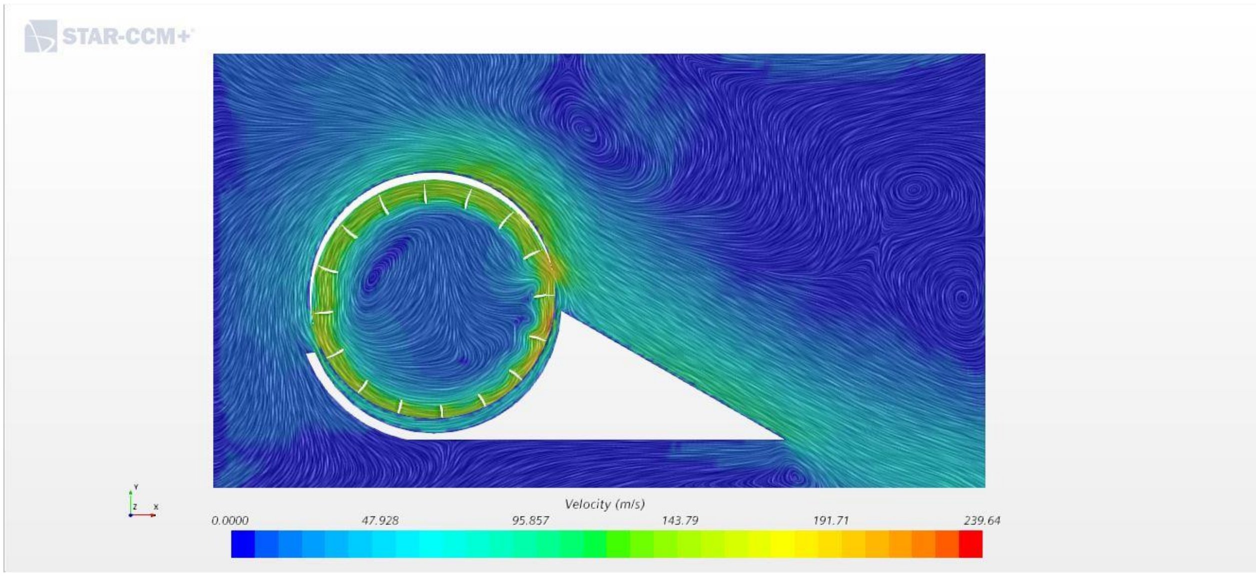


Figure 6: The velocity scalar scene the FanWing CFD at mid-span is shown.

Across the span length, a unique phenomena is observed with regards to velocity exiting the FanWing rotor across the span. From quarter span to three-quarter span the exit velocity of the FanWing remains relatively constant, however, the velocity decreases dramatically beyond these lengths. This phenomena will affect the traditional Lifting Line Theory assumptions of a constant velocity over the wing; hence it is to be expected to receive results that are not in accordance with Prandtl's Lifting Line Theory in these areas. Figure 7 below displays this phenomena in the velocity scalar scene.

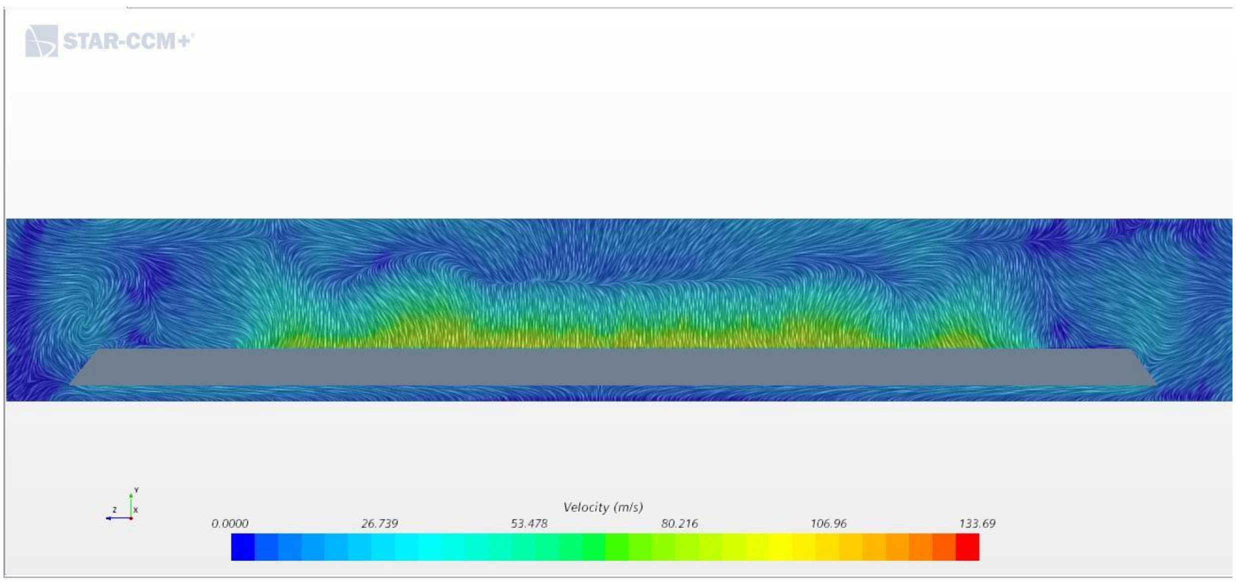


Figure 7: The velocity scalar scene the FanWing CFD from the rear of the wing. The scalar displayer plane goes vertically through the three-quarter chord length, since that is the velocity of interest for the LLT development.

Seeing the following results, it would be expected that the calculated lift distribution is in accordance with Prandtl's LLT assumptions in from a quarter of the way down the span length, to three-quarters down the span length. Because the solution is unsteady, the FanWing lift calculations oscillate through delta time. This has been observed in other papers [16], and the solution was to obtain a time averaged value through the oscillation. Hence, data was collected from .21 seconds to .26 seconds, with the lift distribution values recorded every .01 second. The results of these values are shown in Figure 8 below.

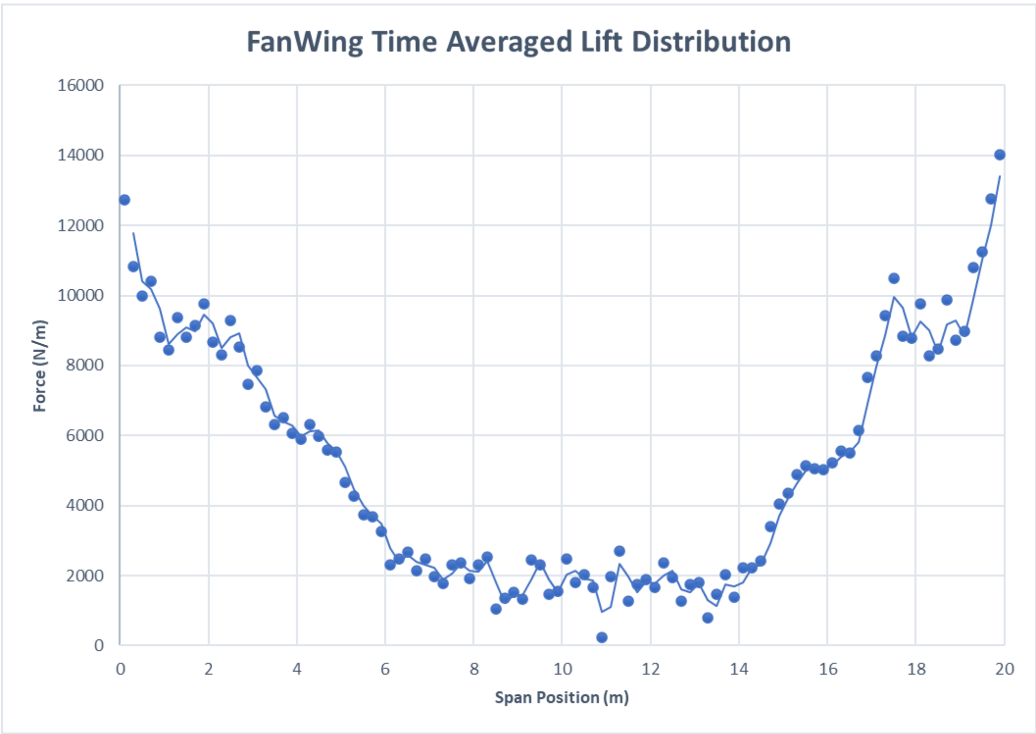


Figure 8: The time averaged lift per unit span from .21 seconds to .26 seconds for the FanWing from the CFD simulation is shown. As it can be seen, the expected lift for Prandtl's LLT breaks down from 0-5 meters and 15-20 meters along the span.

If Prandtl's Lifting Line Theory were to be applied to a traditional wing planform, such a result would be considered erroneous. However, this is consistent with what was observed in the scalar velocity CFD at three-quarter chord, where the velocity across the span was not relatively constant. Where the velocity diverged, the expected solution also diverges. This is where the assumptions made by Prandtl's Lifting Line Theory would break down. Hence, a numerical solution would also not be valid within such ranges.

Numerical Solution Results

After reviewing the CFD results, it is expected that a numerical solution cannot fully account for the entire span of the wing; however, from quarter chord to three-quarter chord the numerical solution would apply. Using the CFD, we acquire the variables needed to run the numerical solver. Through the use of a probe located at the three-quarter chord, the variables V_{tot}, $\alpha_{i, FW}$, $V_{FW,y}$, and $V_{x, tot}$ are obtained. The results are put into the numerical solver and compared with the FanWing lift distribution data. After applying a correction factor of 0.5 to the lift distribution, the following results were obtained as shown in Figure 9. The lift per unit span aligns with the results of the CFD solution from quarter span to three-quarter span, with L' being roughly 2000 N/m, but the numerical solution diverts from the CFD solution otherwise, as expected.

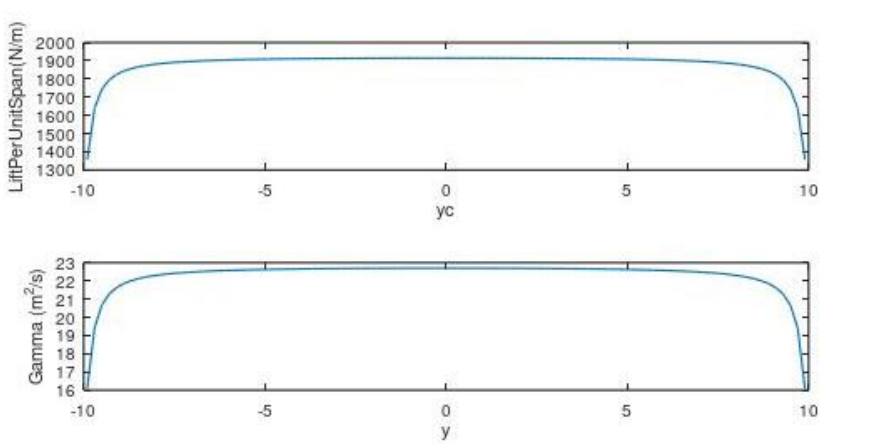


Figure 9: The lift per unit span, and Γ derived from the numerical solver are shown.

CHAPTER FOUR: DISCUSSION

After reviewing the results, there several observations to be made, and various steps in the future that should be undertaken. With regards to the validity of the method of adding an $\alpha_{i,FW}$ to the total calculation, it can be seen that the CFD aligned with the numerical method after adding a correction factor of 0.5 to $\alpha_{i,FW}$. Because the developed LLT theory used to derive the $\alpha_{i,FW}$ was a hypothesis, this may be due to an unaccounted for α_i that must be taken into account due to the FanWing's method of propulsion. Because no theory has been developed to account for the rotation of such blades using Prandtl's Lifting Line Theory, there is limited literature with which to consult for development of Prandtl's Lifting Line Theory. It can be concluded, however, that the speed at which flow is forced over the wing due to the FanWing propulsion system does influence the lift generation, and thus the lift distribution over the FanWing. Increasing rotor speed would increase $\alpha_{i,FW}$, and subsequently increase the lift generated over the wingspan. To test the usage of the correction factor, the study should be repeated at various angles of attack, and the numerical solver should be compared with the CFD solution. This would produce a function where the lift distribution can be found simply through the numerical solver, rather than through a CFD solution, which requires far more computational power and time. Perhaps through this study, the source of the induced α that necessitates a correction factor on $\alpha_{i,FW}$ can be found.

The most significant finding from this study would be the 3D lift distribution found for the FanWing propulsion system. There is sparse data in the literature with regards to a CFD study which investigates 3D lift distribution for a FanWing. All Computational Fluid Dynamics studies done previously have only accounted for 2D lift produced by the FanWing. While the 2D case is valuable, a full understanding of the flight characteristics of the FanWing necessitates an understanding of the 3D lift generation characteristics. The most striking result is the lift generation character from the tip of the wing to 5 meters down the span. While the author, on previous FanWing CFD studies, has seen less pronounced characteristics like these on low aspect ratio FanWings, the rapid rise in lift generation near the end of the FanWing span has not been seen previously. The high aspect ratio may be a contributor to such a finding. It is unknown why this phenomena is generated however, and this itself is worth its' own investigation. The CFD simulation performed did not include the usual rotor hubs seen on FanWing prototypes, which in effect act as winglets; therefore, it would be interesting to observe the effect that the rotor hubs have on this observed phenomena, especially with a high aspect ratio wing. This could lead to the development of an optimal rotor hub which both accommodates the necessary motor and keeps lift generation optimal.

Such a study is an important step in the process to commercially develop the FanWing beyond the prototyping stage. Understanding the 3D lift distribution characteristics informs everything from structural concerns to optimal flight conditions. Because power savings is an important advantage that the FanWing offers, it is important to understand the optimal rpm in various scenarios, which is a parameter which can be informed by 3D lift distribution. The findings here can also inform the structural considerations from wing loading that would be present in full scale prototypes.

CHAPTER FIVE: CONCLUSION

The study conducted demonstrates that a development of Prandtl's Lifting Line Theory has merit to explain the 3D lift generation phenomena for the FanWing propulsion system; however, other factors must be taken into account for a comprehensive solution to 3D lift distribution over a FanWing. This is to be expected given the complex nature of the flow. It can be concluded that the FanWing lift per unit span will follow the modified Lifting Line Theory numerical method, when a correction factor is applied, within the span of the wing which adheres to LLT assumptions. It was demonstrated that the numerical solver misses variables, likely an induced α, which have yet to be studied due to the FanWing's unique method of propulsion. In the future, a comprehensive study over multiple angles of attack can resolve the lift distribution discrepancy through the application of a correction factor which is a function α. Such standards could be helpful in determining optimized performance for a FanWing at various flight conditions.

The lift distribution results which are documented in this study are the first CFD investigation into the three-dimensional lift characteristics of FanWing propulsion. Such results give a baseline by which other studies can be compared. It is important to note the necessity of using a time-averaged lift distribution value, as the lift distribution varies in an unsteady solution, as would be expected. In future studies, it would be notable to document the effect of the rotor hubs that are generally present in prototypical FanWings as opposed to the lift distribution without the rotor hubs. The three-dimensional CFD methodology given here built upon the methodology from the two-dimensional cases in literature, and it showed them to be reasonably valid for the 3D case as well. The findings given here show that a mere two-dimensional representation of the FanWing in CFD, while helpful, misses various 3D effects of FanWing lift generation. Therefore, in future CFD studies of the FanWing, a study should include both 2D and 3D cases in order to be considered comprehensive.

While the CFD and numerical LLT numerical solution developed here only align after the application of a correction factor, it is to be expected that a flow as complex as the FanWing's cannot be fully characterized in LLT by the velocity vectors at three-quarter chord. However, there is indeed merit to the solution obtained. In future development, a means of rectifying this discrepancy should be developed, through either a correction factor as a function of α, or another parameter which corrects for the total induced angle of attack on the FanWing.

The FanWing is still a novel concept with much work to be done with theoretical and practical development. The work given here is another step to building an understanding of the physical phenomena pertaining to this unique propulsion system. Once an understanding of the FanWing is sufficient, it is hoped that commercial development may occur, which would create a new class of aircraft which performs more efficiently and effectively in specific flight envelopes than current aircraft platforms.

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