A Brief Review on Potential Flow Solver Techniques Used for Studying Stalling Conditions of the Aircraft Wings in Multiple-Lifting-Surface Configuration

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Abstract

Of the many phases of flight conditions encountered in mid-air, there is seldom anything more frightening than stall as the forces acting on flight post-stall quickly renders aircraft as a huge aluminum structure obeying the commands of gravity. In the present work, a short review of literature related to time to time efforts being made in order to understand the flow behavior over the aircraft wings in multiple lifting surface configuration and the stall characteristics of formation flight using various potential flow solver techniques.

Keywords: wing, unsteady aerodynamics, potential flow, stall, formation flight, VLM, decambering approach, lift.

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INTRODUCTION

In the first course of aerodynamics, the idea is acquainted with the motion of a body in air medium and the way it interacts with the air flow. This basic thought presides over the other principles in regard to the subject matter. Over past a century there have been numerous ventures passed on to understand the mystery behind the flow structure and its tendency to get hold of the body under consideration.

The content available for the study of aerodynamics stands on the works of many who had the strong intuition about the flow maneuverability. The credit for early development of wing theory is highly reserved for the pioneers namely, Frederick W. Lanchester, Francis Wenham, Ludwig Prandtl, Glauert, Helmholtz, Max Munk, Albert Betz, V. M. Falkner and many others. As the physicists realized the changes in flow behavior explained through fluid mechanics especially, hydrodynamics point of view, the desire to obtain the optimum numerical techniques was encouraged for precise modeling of the flow.

IMPROVEMENTS IN PRANDTL'S LIFTING LINE THEORY

An article by E. Pakalnis [22] (2004), gives an account of numerous developments in calculation method of wing characteristics. With a spur of moment, the fluid mechanics as a whole was revolutionized soon after the remarkable presentation by Ludwig Prandtl [37] on boundary layer concept on 8 August, 1904. Although, the vortex theory of wings was first expressed by Frederick W. Lanchester [37] in his two-volume work, Aerial Flight in 1907, but it was soon discarded. Later, Ludwig Prandtl [37] in 1918–1919, confirmed the correctness of his work and founded the concept of classical lifting line theory (LLT) that could predict the flow past an unswept wing of medium to high AR in an incompressible flow. Prandtl's LLT was influenced by Lanchester's work and later became a standard tool for computing wing aerodynamics. It was able to provide linear solutions for the flow problems at small angles of attack. [37]

Later, Tani [1-22] (1934) developed the first successful method to handle non-linear section lift curve slopes in LLT formulation, upto the onset of stall. Meanwhile, for high α, Von Karman [1-22] noticed non-unique solutions through Prandtl's LLT for symmetric geometry indeed as well as for the onset flow conditions. It included both symmetric and asymmetric lift distributions at zero yaw. Influenced by Tani's work, Schairer, [1-22] under the guidance of Sears, [1-22] developed a trial-n-error iterative procedure led to solutions at partially-stalled cases which were not feasible earlier by Tani's successive approximation method. His results provided the solutions containing asymmetric lift distributions (in addition to a classical symmetric solution) with largely connected rolling moment for a small α - sequence just beyond the stall.

Long before, J. D. Anderson *et al.* [38] (1979) successfully obtained an iterative numerical solution using classical LLT to post-stall angles on drooped L.E. wings. Mc Cormick [24] (1989) developed a method for applying 2D Kutta-Joukowski law to the 3D flow for a single-lifting surface with straight lifting line, neglecting CFD type of calculations. Another research paper by him dated back to year 1968 that emphasizes on aircraft trailing vortex system involving actual flight testing in a method that could predict the flow velocity of trailing vortices in decay state downstream of the test aircraft up to distances of 1000c approximately, assuming similar geometric conditions. Unlike above attempts of lift prediction based on temporal change, paper by Phillips [21] and Snyder [21] (2000) accounts on using a Fourier-series solution in LLT to study rigid body roll and small-angles 3D wing flapping, which perhaps results in no net effect on the mean lift. In recent years, classical theory is extended for discrete vortex lattice assumptions instead of a single lifting-line model as discussed in the following.

DEVELOPMENTS IN VORTEX LATTICE METHOD

The current research endeavors to model the potential flow governed by Laplace equation which is a second-order PDE. Since, many such mathematical models of fluid dynamics can be expressed as PDEs, the evaluation of modern potential-flow solver techniques can be dated relatively long time back, when L.F. Richardson [23] in 1910 published a paper regarding the foundation of modern numerical analysis of PDEs as declaimed by Bart Rademaker [23] in his NASA Langeley Workshop, 1976. He also mentioned about several other pioneers including- Prandtl [22] (1918) for LLT, Liepmann [23] (1918) for improving convergence rate of Richardson's procedure, A. Thom [23] (1928) for first numerical solution of viscous FD problem, E. Pistolesi [23] (1937) for "1/3-3/4 rule", Weissinger [23] for implying it on a 3D wing and many others. The so-called Finite-step method or Vortex-step method stands on the works of Mutterperl [23] (1941) and Weissinger [23] (1942). Later, Cambell (1951) and Blackwell [22] (1969) simplified the method assuming constant strength of each vortex.

Rademaker [23] pointed out the early attempts promoting computational techniques in Fluid dynamics with the term 'Vortex lattice method' that was first coined by V. Falkner [23] in the year 1947. Falkner's method was widely accepted throughout in 1950's, however, its large calculation effect limited the number of panels and hence, deluded the accuracy level. Later, Harlow and Fromm [23] improved VLM for computer capability in their paper published in the year 1965. In the same year, Hedmen [35] applied computer code for VLM to calculate quasi-steady state loadings on a thin elastic wing in subsonic flow. His results correlated successfully with those of other lifting methods. In succeeding years, CFD had been largely overwhelmed by the use of VLM due to its computational speed as well as its versatility in complex configuration designs and in mathematical model complexity of the panel flow.

Paper by James [11] (1972) indicates on the phenomenal use of VLM in general, while accuracy is satisfied. Cauchy-type singular kernals are taken up in the governing integral equation for 2D thin wing theory, discretized for the Hilbert Transform and compared with appropriate analytical solutions. It also discusses about the distance between 'vortex' point and 'sense' point (or collocation point) and suggests that influence coefficient matrix is never singular for these two choices of spacing parameters. Paper recommends on the use of E. Pistolesi [23] "1/4-3/4" rule since spacing give exact correlation of lift and moment for constant downwash (flat plate). Sarpakya [12] (1976) developed a 2D discrete vortex shedding model past an inclined wing using appropriate complex-velocity potential, Kutta condition and Jowkowsky transformations. The kinematic and dynamic features of the flow obtained for different angles of attack were 20 to 25% more accurate than the experimental results for large Reynolds number.

Piszkin & Levinsky [10] (1976) developed a computer code based on a part of iterative procedure primarily conceived by Tani, using discrete vortex method based on classical LLT assumptions in order to predict time-dependent longitudinal and lateral characteristics of various wing-body configurations of moderate AR, at post-stall α. Their numerical simulation worked well to predict non-linear lift hysteresis during stall, loss of roll control reversal, wake effect, changing AR, wing rock & drop and even at zero-β rolling & yawing moment.

Paper by Rossow [40] (1995) emphasizes on the accuracy check on VLM in computing loads induced on aircraft when wake encounters. The results are in agreement with the wind-tunnel results as long as trail wing span is less than about 0.2 of the generator span. Beyond this, VLM code is seen to over predicts the loads by increasing amounts. Influenced from Ref [12] Dovgii and Shekhovtsov [13] (2001) presented an improved VLM (IVLM) as an economical method for removing arbitrariness in VLM parameters which thereby helps in decreasing the discretization error if occurs. This readily, results in the solution that converges from numerical point of view.

Mukherjee1 and Gopalarathanam [1] (2004) devised a novel approach called 'Deacambering Approach' to enhance VLM code for camber reduction and prediction of force and moments coefficients over a range of angles of attack of wing in symmetric flight conditions. The approach worked exceptionally well for the post-stall angles of attack. It is somewhat similar to the idea used in the paper by Lan [39] (1973), however, in his work, only chordwise vortex integral was reduced to a finite sum through a modified trapezoidal rule as well as Chebyeshev polynomials and spanwise vortex distribution was taken as the stepwise constant unlike in the former research. Paper by Spyros [17] (2006) detects the peculiarities in VLM code mainly when concerning the same problem of limiting scope for post-stall angles, in rotor problems and for 2D turbulent flows.

Bramesfeld and Maughmer [16] (2008) modified VLM code to model lifting surfaces and their shed wake. The method is considered superior over the other potential flow methods because of its robustness which is achieved without the relevant solution being dependent on the choice of a cut-off distance or core-size. Other factors are also majorly accounted such as computational speed and its ability to predict the loadings at discrete points accurately. Melin [36] (2000) developed an enhanced version of VLM code in MATLAB termed as, 'TORNADO' to compute aerodynamic coefficients and stability derivatives up to the stall angles with higher accuracy. The method was implemented for different aircraft geometrical conditions as a real-time application but its capacity is examined to follow time-independent constraint.

REVIEWS ON FORMATION FLYING

The present research concentrates on the change in aerodynamic coefficients for tandem wing configuration. More than longitudinal distance the lateral distance of the wings dominates largely the flight stability and also affects the total flight power reduction of the whole formation. The theory of multiple lifting surfaces probably has been an extensive research prospect ever since, Max Munk [31] (1976) combined multiple wings to a multiplane in a 2D flow field and computed at each point the transverse velocity distribution along parallel lines using mathematical expressions. D. Hummel [18] (1983) in his paper explained the various features of formation flight of birds and its imitation for unmanned aerial vehicles (UAVs). He applied the theoretical aerodynamic methods to calculate flight power reduction for arbitrarily shaped flight formations with any number of birds. Physically, some minor portion of twist is suggested to fly in a formation without rolling moments, however, for such case, flight speed has been still as lower as compared to individual flight.

Fanjoy and Dorney [42] (1997) studied tandem 2D symmetrical wing interaction in different flow regimes as well as unsteady effects due to angular disturbance and change in flow velocity. Authors used computations to correlate lift/drag ratios for the two wings at subsonic and sonic speeds. And, results suggested very little aerodynamic benefit for very large or very small lateral displacements.

Blake and Multhopp [41] (1998) explored the issues of indefinite weight and fuel consumption across the formation using VLM techniques for viscous flow conditions. The wings are assumed to be in V-formation and the study has been carried out to calculate their induced drag and lift values for temporal and spatial changes. Blake together with Gingras [29] (2001) published paper regarding wind tunnel test of tandem delta wings and compared the results with VLM-based predictions. Lift to drag ratio has been seen to increase on overlapping the wing tips. A maximum induced reduction of 25% is measured on the trail wing compared with 40% predicted reduction.

Brent and Vachon [24-25] (2002-03) carried the flight performance tests of two tandem F/A- 18 aircrafts including drag and fuel flow reduction and improvements in range factor, when trail aircraft was placed for desired test condition of approx. 30 sec for each test point. [10] Drag is suggested to be reduced by 20% and fuel flow by 18% at flight conditions of Mach 0.56 and an altitude of 25,000 ft. However, at Mach 0.8, and altitude 40,000 ft., fuel flow is reduced by 14% when compared with that of a controlled chase airplane of similar configuration.

Recently, Ghommenn [34] (2013) carried the similar objective considering flapping wings flight. Fritz and Long [14] (2004) used UVLM to model the finite wing motion in contrast to bird's flapping flight and generated wake through it. The models include free-wake relaxation, vortex stretching, and vortex dissipation effects and object-oriented computing tools are employed, simulating features of complex flapping flight. Gibbs [28] (2005) tested large AR swept wings at low Reynold's no. and higher velocities. Author used experimental methods to determine trailing vortex strengths, total lift and lift distributions for 3D wings of different cambers in close proximity and the results were verified with the existing literature.

Chichka and Speyer [32] (2006) proposed a new method of peak-seeking control using a Kalman filter to obtain characteristics of drag reduction applying the realistic aircraft dynamics and including the dominant non-linear terms due to the aircraft interaction. Bramesfeld and Maughmer [16] (2008) also treated the high AR wings in different configurations considering wake-roll up. In all cases the aircraft were trimmed for roll and trail aircraft pitch motion was adjusted to match the lift coefficient of the lead aircraft.

Saban [27] (2009) in his thesis devised a novel method Wake Vortex Model (WVM) integrated within a Matlab/Simulink simulation environment to process the ELL code (based on Weissinger's extended LLT) for wake vortex modelling simulate during formation flying of UAVs. Influenced by [32], Hemati [30] (2012) introduces a wake-sensing strategy for depicting wake position and its strength in a tandem aircraft configuration.

Hussain [2] (2012) explored unsteady flow analysis past the two airfoils suddenly set into motion using Lump vortex model and computed steady-state flow problem at each time-step, using no-normal boundary condition. In the meanwhile, the wake-vortex position is updated at each time-step to predict wake shape. In a recent paper by Mukherjee [3] (2014) extended the use of 'Decambering' technique in VLM code which uses a modified NACA 2412 airfoil data for post-stall lift and moment predictions over two Cessna 172 aircraft surfaces in echelon formation because the experimental results of Bangesh [33] (2006) does not contain 2D data to be verified, thus the wind-tunnel data for NACA 2412 airfoil is taken to verify 3D wing results.

REFERENCES

1. Dr. R. Mukherjee, Dr. A. Gopalarathnam, Post-Stall Prediction of Multiple-Lifting-Surface Configurations Using a Decambering Approach, *J. Aircraft*, 2004.
2. Hossain Aziz & Dr. Rinku Mukherjee, Unsteady Aerodynamics of Multiple Airfoils in Configuration, Intl. *J Adv Comp. Sci*., 2012; Vol. 2(11), 399-411pp.
3. Gunasekaran M. and Dr. Rinku Mukherjee, A Numerical Study of the Aerodynamics of Cessna 172 aircrafts in Echelon formation, 52nd Aerospace Sciences Meeting, AIAA Conference, (January 2014)
4. John. D. Anderson, Fundamentals of aerodynamics, 3rd edition, Tata McGraw-Hill publications. (2001)
5. John J. Bertin and Russell M. Cummings, Aerodynamics for Engineers, 5th edition, Prentice-Hall, Inc (1979)
6. L.J. Clancy, Aerodynamics, 1st Edition, Pitmann Publications Limited, London, (1975)
7. Robinson & J.A Laurmann, Wing Theory, Cambridge University Press, (1956)
8. Joseph Katz and Allen Plotkin, Low speed aerodynamics, 2nd edition, Cambridge University press. (2001)
9. Arnold M. Kuethe and Chuen-Yen Chow, Foundation of Aerodynamics, Bases of Aerodynamic Design, 5th Edition, John Wiley & Sons Inc., New York, (2000)
10. S.T. Piszkin & E.S. Levinsky, Nonlinear Lifting Line Theory for Predicting Stalling Instabilities on Wings of Moderate Aspect Ratio, Naval Air and Development Centre, Code 3015, Warminster, PA 18974, (15 June, 1976)
11. Richard M. James, On remarkable accuracy of the vortex lattice method, Computer methods in applied mechanics and engineering, 1 (1972)
12. Turgut Sarpkaya, An inviscid model of two-dimensional vortex shedding for transient and asymptotically steady separated flow over an inclined plate, Journal of Fluid Mechanics, Vol. 68, part 1, Pp. 109-128 (1975)
13. S.A. Dovgii and A. V. Shekhovtsov, An improved vortex lattice method for stationary problems, *J Math Sci*, 2001; Vol.104(6).
14. Tracy E. Fritz and Lyle N. Long, Object-Oriented unsteady vortex lattice method for flapping flight, *J. Aircraft*, 2004;Vol. 41(6).
15. Gotz Bramesfeld and Mark Maughmer, Related-wake vortex-lattice method using distributed vorticity elements, Journal of aircraft, Vol.45, No.2, (March-April 2008)
16. Gotz Bramesfeld and Mark Maughmer, Effects of wake roll up on formation flight aerodynamics, Journal of aircraft, Vol.45, No.4,(July-August 2008)
17. Spyros G. Voutsinas, Vortex methods in aeronautics: how to make things work, International Journal of Computational Fluid Dynamics, Vol. 20, No. 1, (Jan 2006)
18. D. Hummel, Aerodynamic aspects of formation flight in birds, XVIII Journal of Theoretical Biology, Moscow, Vol. 104, No. 3, pp 321-347, (October 7, 1983)
19. Enrique Mata Bueso, Unsteady aerodynamic vortex lattice of moving aircraft Aeronautical and Vehicle engineering department, KTH, Sweden, (September 30, 2011)
20. Joseba Murua, R.Palacios, J. Micheal R. Graham, Applications of the unsteady vortex-lattice method in aircraft aeroelasticity and flight

dynamics, Progress in Aerospace Sciences 55, Pp. 46 – 72, (2012)
21. W.F. Phillips & D.O. Snyder, Modern Adaptation of Prandtl's Classical Lifting Line Theory, Journal of Aircraft, 38th AIAA Aerospace Sciences Meeting & Exhibit, Reno, NV, Vol. 37, No. 4 (January 12-14, 2000)
22. E. Pakalnis, Lift and drag force calculation methods using non-linear section data. History and recent research, Aviation, 8:2, (2004)
23. Bart Rademaker , Vortex Utilization Method Historical evolution of VLM, Workshop at NASA Langeley Centre, Hampton, Virginia, (May 17-18, 1976)
24. Barnes W. Mc Cormick, Structure of Trailing vortices, Journal of Aircraft, Vol. 5, No. 3 (May-June 1968)
25. R. J. Ray, B. R. Cobleigh, M. J. Vachon and Clinton St. John, Flight Test Techniques Used to Evaluate Performance Benefits during Formation Flight, NASA Dryden Flight Research Center, Edwards, California (August 2002)
26. M. J. Vachon, R.J. Ray, K. R. Walsh and K. Ennix, F/A-18 Performance Benefits Measured during the Autonomous Formation Flight Project, NASA Dryden Flight Research Center, Edwards, California (September 2003)
27. Deborah SABAN, Wake vortex modeling and simulation for Air Vehicles in Close Formation Flight, Cranfield University, (January, 2010)
28. Jason Gibbs, Experimental Determination of Lift and Lift Distributions for Wings in Formation Flight, Virginia Polytechnic and State University, (January, 2005)
29. W. B. Blake & D. R. Gingras, Comparison of Predicted and Measured Formation Flight Interference Effects, AIAA Atmospheric Flight Mechanics Conference Paper, AIAA-2001-4136, (August 2001)
30. Maziar S. Hemati, Wake Sensing for Aircraft Formation Flight, Journal of Guidance, Control and dynamics, (2012)
31. Max M. Munk, Elements of the wing section theory and of the wing theory, Report 191, NASA Technical Documents, (December 1, 1979)
32. D.F. Chichka and J. L. Speyer, Peak-Seeking Control for Drag Reduction in Formation Flight, AIAA Journal of Guidance, Control and dynamics, (2006)
33. Z. A. Bangash & M. J. Khan, Aerodynamics of Formation Flight, Vol. 43, No. 4, Journal of aircraft, (July-August 2006)
34. Mehdi Ghommem & Victor M. Calo, Performance Analysis of Flapping Wings in Formation Flights, 2nd ECCOMAS Young Investigators Conference 2013, Bordeaux, France (September, 2013)
35. S. G. Hedman, Vortex Lattice Method for Calculation of Quasi Steady state loadings on thin Elastic wings in Subsonic flows, FFA Aeronautical Research Institute of Sweden, Stockholm, Report 105, (1966)
36. Tomas Melin, A Vortex Lattice MATLAB Implementation for Linear Aerodynamic Wing Applications, Royal Institute of Technology, KTH, No. 45, (2000)
37. John David Anderson, History of Aerodynamics and its Impact on flying machine, Cambridge University Press (1997)

38. J. D. Anderson Jr., Stephen Corda & David M. Van Wie, Numerical Lifting Line Theory applied to Drooped Leading Edge Wings Below and Above Stall, AIAA Journal of Aircraft, Vol. 17, No.12, (1979)
39. C. Edward Lan, A Quasi-Vortex Lattice Method in Thin Wing theory, AIAA Journal of Aircraft, Vol. 11, No. 9, (1973)
40. Vernon J. Rossow, Validation of Vortex-Lattice Method for Loads on Wings in Lift-Generated Wakes, AIAA Journal of Aircraft, Vol. 32, No. 6, (1995)
41. William Blake & D. Multhopp, Design, Performance and Modeling Considerations for Close Formation Flight, Journal of Aircraft, AIAA-98-4343, (1998)
42. David W. Fanjoy & D. J. Dorney, A study of tandem-airfoil interaction in different flight regimes, AIAA Aerospace Sciences Meeting & Exhibit, 35th, Reno, NV, (January 6-9, 1997)
43. James C. Sivells and Robert H. Neely, Method for calculating wing characteristics by lifting-line theory using nonlinear section lift data, NACA Washington D. C., Technical note no. 1969, (April 1947)

