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DIRECT SIMULATION (MONTE CARLO) OF DELTA WINGS IN THREE–DIMENSIONAL, NEAR–CONTINUUM, SUBSONIC FLOWS

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ABSTRACT

Three-dimensional simulations of subsonic flow about delta wings are performed using the Direct Simulation Monte Carlo method of Bird. The position and interaction of leeward-surface vortices are investigated to benchmark the applicability and accuracy of the method at low speed in three dimensions. Using an infinitely thin delta wing the effect of angle of attack, wing vertex angle, Knudsen number and boundary conditions are investigated. The method qualitatively reproduces the delta wing vortical structure, but in a quantitative sense, the lift coefficient is lower than experimental results by a factor of two. Employed in this research is an adaptive subcell regridding scheme which significantly enhances the accuracy of the simulation.

NOMENCLATURE

α	angle of attack
λ	mean free path
Λ	wing vertex angle
b	wing semi-span
c	wing chord
C_L	Lift coefficient
C_P	Pressure coefficient
Kn	Knudsen number
M	Mach number
Re	Reynolds number – $Re = 16M/(Kn\sqrt{30\pi})$ [1]

Subscripts

$_{o,\infty}$	freestream conditions

INTRODUCTION

The accurate calculation of vortical flows is a very important yet challenging task in the design of modern high-speed aircraft that are required to maneuver at high angles of attack. The flow about these aircraft with a delta wing planform at angle of attack is characterized by the presence of large spiraling vortices on the lee side of the wing.

A flat-plate delta wing with sharp leading edges presents a simple configuration for the study of vortical flows. At sufficiently high angles of attack the dominant feature of flows over such wings is a pair of counter-rotating vortices, known as primary or leading-edge vortices. In many cases, these vortices are the primary structure in the flow affecting the performance of the aircraft.

These vortices form over the upper surface of the wing as a result of the roll-up of the vortex sheet shed from the leading edges. The flow induced by these primary vortices can separate near the wing surface due to the adverse pressure gradient the flow encounters in the spanwise direction. This separated flow may then form an oppositely rotating secondary vortex, which tends to move the primary vortex inboard and away from the wing upper surface. These secondary vortices can also form tertiary vortices by the same process.

Flows over slender subsonic and supersonic delta wings have been studied experimentally by Monnerie and Werle[1], Hummel[2], Miller and Wood[3], and Stallings and Lamb[4], among others; they have been studied numerically by Rizetta and Shang[5], Buter and Rizetta[6], Thomas and Newsome[7], Webster and Shang[8], Thomas et al[9], McMillin et al[10], Rizzi et al[11], Fujii and Schiff[12], Ekaterinaris and Schiff[13], Vadyak and Schuster[14] and Agrawal et al[15], to name a few.

CURRENT RESEARCH

The primary objective of this research is to demonstrate the ability of the direct simulation Monte Carlo (DSMC) of Bird[16] to accurately predict three dimensional delta wing vortex formation and development at subsonic speeds in near-continuum flow. The basic flow geometry considered is a delta wing with infinitesimal thickness with a symmetry plane used to halve the flowfield size. The application of molecular simulation methods to this problem is relatively straightforward but has not been attempted until now.

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The advantage of a numerical simulation is the availability of details on all aspects of the flow for every stage of the flow development, and information is easily extracted from the simulation data files on a variety of parameters.

A recent study by Bird[17] of two-dimensional flat plate vortex streets indicates that the DSMC method can model unsteady vortical flows in two dimensions in a qualitative sense, and further work by Talbot-Stern[18] enhanced the quantitative accuracy. The current research in three-dimensions requires significantly more computational power and memory, stretching the existing resources to the limit.

In this study, DSMC computational simulations were performed of the vortex shedding phenomenon at a range of varying flow conditions, including angle of attack, Knudsen number, wing vertex angle and boundary conditions. The effect of these parameters on the vortex position and stability were investigated.

A 'control' case was established, against which the effects of all parameter changes were compared and measured. The computational facilities were not capable of integrating improvements in all parameters, so this piecemeal approach was used. The trends due to variation in the parameters were investigated which indicate that, once sufficient, affordable computational power is available, the DSMC method will be able to quantitatively predict delta wing vortices in three dimensions.

DELTA WING AERODYNAMICS

The dominant aspect of delta wing flow is the vortex pattern that occurs in the vicinity of the highly swept leading edges. This vortex pattern is created primarily by flow separation along the sharp leading edge. This separated flow curls into a primary vortex which exists above the wing just inboard of each leading edge. Secondary vortices may also be present as illustrated in Figure 1. The results of a DSMC simulation are presented in Figure 2, with the primary vortex clearly visible forming at the leading edge and growing in size towards the trailing edge, finally dissipating past the end of the wing.

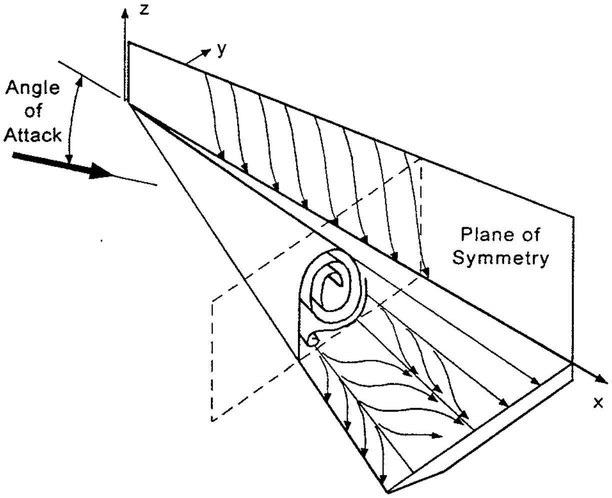


Figure 1: General subsonic flowfield structure over the top of a delta wing at angle of attack.

The leading-edge vortices are strong and stable. Being a source of high energy, relatively high-vorticity flow, the local static pressure in the vicinity of the vortices is small. Hence, the surface pressure on the top surface of the delta wing is reduced near the leading edge and is higher and reasonably constant over the middle of the wing.

The spanwise variation of pressure over the bottom surface is essentially constant and higher that the

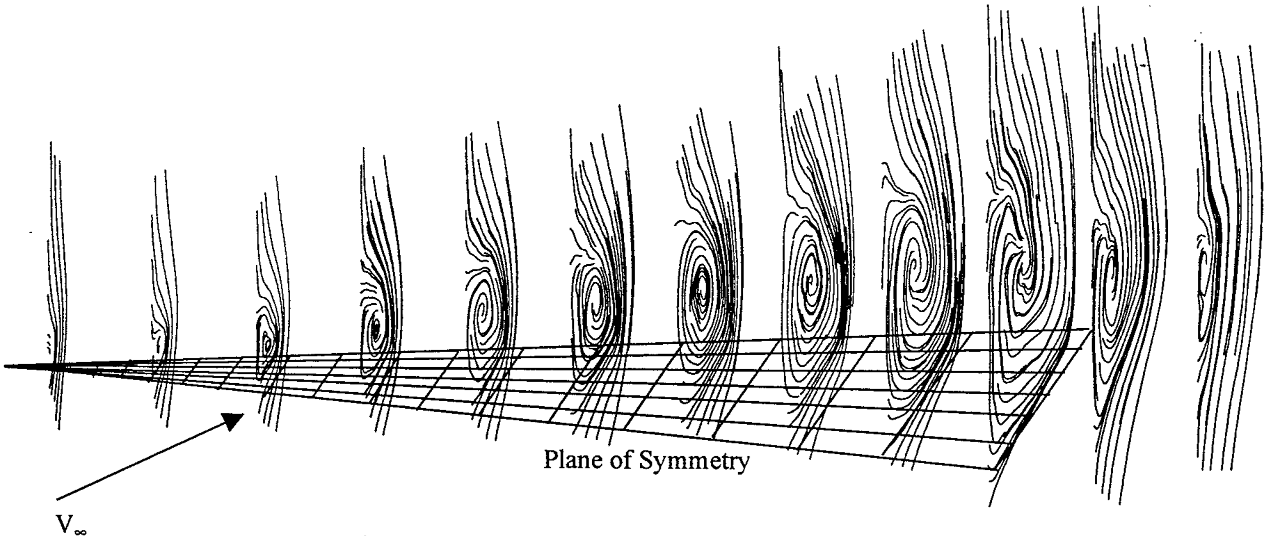


Figure 2: Vortex structure for $M_\infty = 0.5$, $\alpha = 30°$, $\Lambda = 74°$.

freestream pressure. Over the top of the surface, the spanwise variation in the midsection of the wing is primarily constant and lower than the freestream pressure. However, near the leading edge the static pressure drops considerably with C_P becoming more negative. The leading–vortices are literally creating a strong 'suction' on the top surface near the leading edge.

Figures 3 and 4 illustrate the theoretical and DSMC pressure coefficient distributions. The DSMC results show good qualitative correlation with the theoretical results.

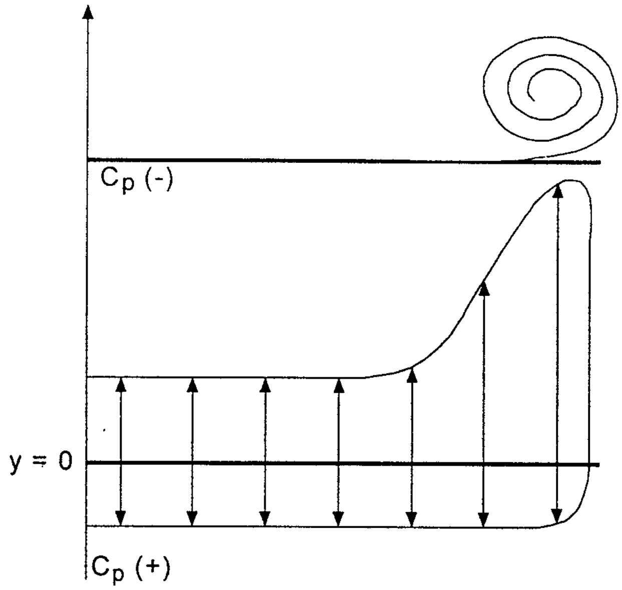


Figure 3: Spanwise pressure coefficient distribution across a delta wing.

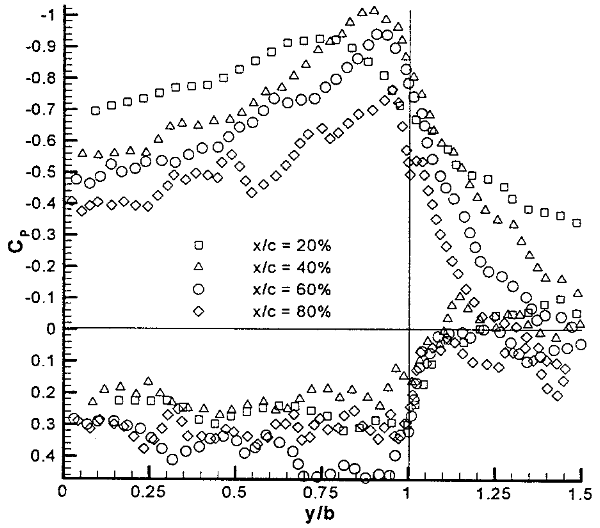


Figure 4: Actual pressure coefficient distribution across a delta wing at several chordwise locations from a DSMC simulation for $M_\infty = 0.5$, $\alpha = 30°$, $\Lambda = 60°$.

SOFTWARE AND SIMULATION GRID SCHEME

DSMC simulations are computationally demanding. The hardware platforms used in this research included Intel 90, 133 and 166 MHz Pentiums with 64 MB RAM. This allowed up to 1,000,000 molecules and 200,000 cells to be simulated. Accurate results for subsonic delta wing vortex formation in three dimensions were obtained within one week on a 166 MHz Pentium.

Rarefaction effects due to insufficient computer resources have complicated previous attempts to model this flow example, yielding excessive simulation times. Faster computers with more memory reduce the time to an acceptable level, but the extra demand of higher grid resolutions and more simulated molecules can result in a sluggish, slow simulation.

One solution, which reduces run times significantly, is an adaptive subcell regridding scheme. This uses a regular, orthogonal cellular mesh, divided into regular, orthogonal subcells, where molecular indexing routines are trivial. While this reduces the accuracy of the cell sampling relative to body conforming grids, the accuracy of the collision routines can be maintained by ensuring that each subcell contains an optimal number of molecules – around two or three – to maintain 'nearest-pair collisions', maintaining the subcell size and mean collision separation at the same magnitude as the local mean free path at the same time.

To guarantee that there is indeed two or three molecules per subcell, the program regrids the subcell mesh at intervals to optimize the subcell resolution to match the local molecular density. The primary advantage of this technique is that it allows accuracy improvements 'on-the-fly' without any change to the cell mesh. Additionally, subcells require a magnitude less of memory storage, permitting significantly higher collision resolutions than are otherwise obtainable. Figure 5 illustrates the layout of the flowfield and Figure 6 demonstrates the optimization of the subcell mesh.

For the simulations, a cellular resolution of 70 x 35 x 50 (122,500 cells) was used. Analytic surface descriptions of flat plates were employed so surface interaction detection and collision algorithms were again trivial.

A resulting benefit from the use of optimally refined subcells is the preservation of angular momentum within the cell, indeed down to a level as small as the subcell. By the use of subcells and a feature to enable subcell mesh refinement, the DSMC program developed by the author optimizes the computer resources available while maintaining correct flow simulation.

SIMULATION CONTROL CASE

This flow simulation investigated the DSMC ‘control’ case. Parameters investigated were. Only one parameter – angle of attack, vertex angle, Knudsen number or boundary condition – was varied at a time for a set of simulations to determine its effect on the flow solution while the other simulation parameters remained unchanged from the control case.

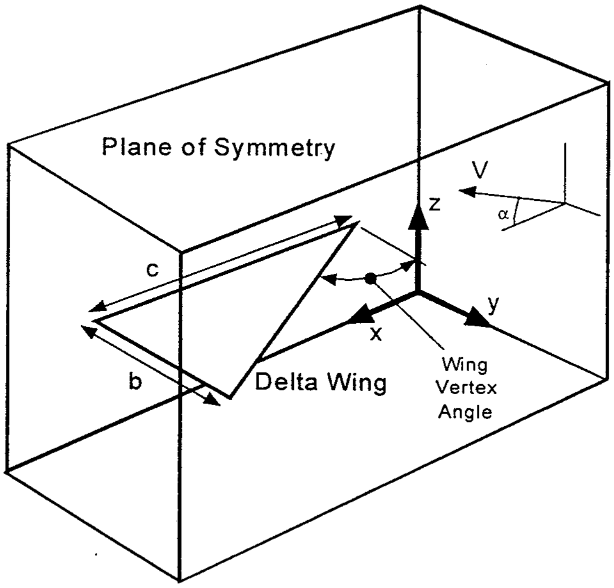
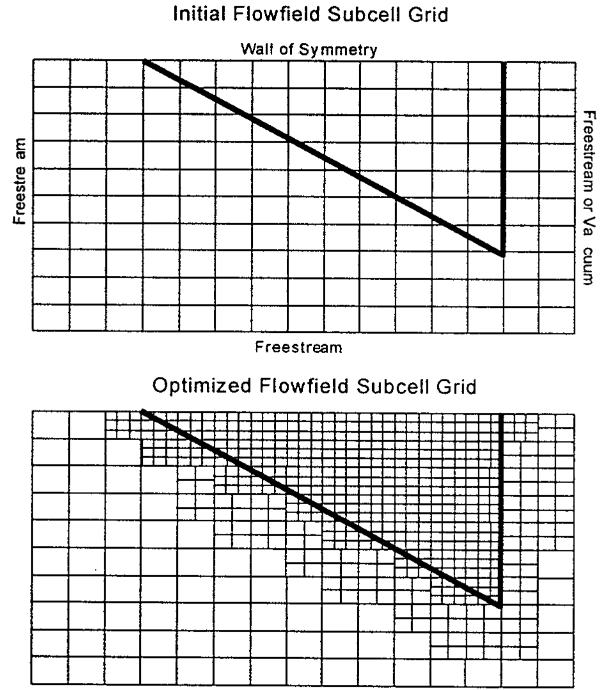


Figure 5: Flowfield setup and relevant dimensions and axes.


Initial Flowfield Subcell Grid

Optimized Flowfield Subcell Grid

Figure 6: DSMC initial and optimized flowfield for a z = constant slice near delta wing position.

The control case is for the flow of monatomic air at $M_\infty = 0.5$ past an infinitely thin, specularly reflecting delta wing with $\Lambda = 60°$ and chord of 860 λ_o and a semispan of 500 λ_o. Based upon the chord, Kn = 0.0012.

The calculation employed the variable hard sphere molecular model for which Reynolds number is related to Mach number and Knudsen number by Equation [1], giving Re = 700 in this case.

The computational flowfield is 1560 x 585 x 1015 λ_o and is divided into 75 x 35 x 50 cells which are, in turn, divided into subcells. The resolution of the subcells is addressed on a cell-by-cell basis during runtime by the subcell regridding routine. The total number of simulated molecules was one million so that the average instantaneous number in a cell was about 8. The flow properties were based upon a time averaged sample once a steady flow condition was obtained.

All boundaries were based upon freestream conditions, except for the plane of symmetry, which was specularly reflective. The use of freestream boundaries may have adverse effects on the flow inside the control volume, so other simulations investigated the flow with different boundary types. Further research is considering the position of the boundaries relative to the delta wing. The use of a symmetry plane reduced the required flowfield size by a factor of two.

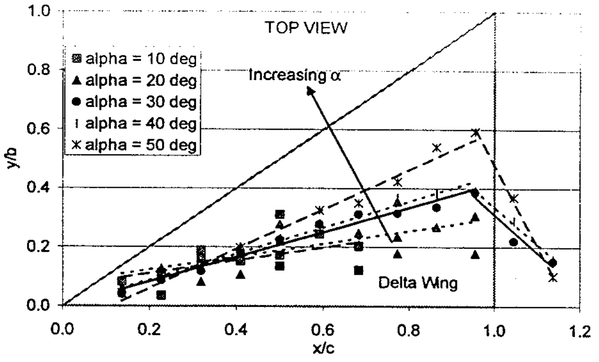
The results presented in the following sections clearly indicate that the DSMC method is capable of qualitatively simulating complex three dimensional flow, specifically the vortical delta wing case. However, the lift coefficient of the control case is 0.6, half of the experimental $C_L = 1.2$ from O’Neil et al[19].

EFFECT OF ANGLE OF ATTACK

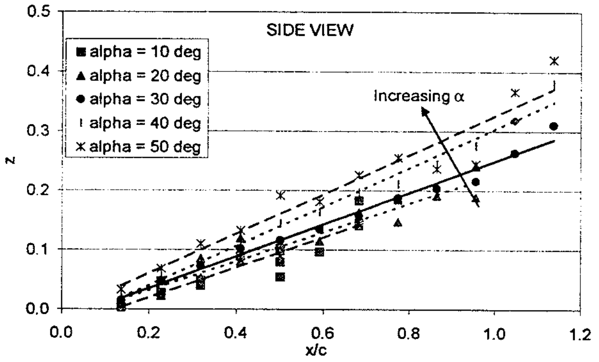
The angle of attack of the delta wing relative to the freestream has a strong influence on the position of the vortex. The angle of attack was varied between ten and fifty degrees.

Figure 7a shows the spanwise position of the vortex core as a function of chordwise location. With increasing angle of attack, the vortex moves outboard. Even at this high angle of attack, the flow structure over the top of the wing was stable and unstalled, highlighting the aerodynamic uniqueness of the delta wing. Towards the trailing edge, the vortex begins to breakdown and the core moves towards the wing centerline.

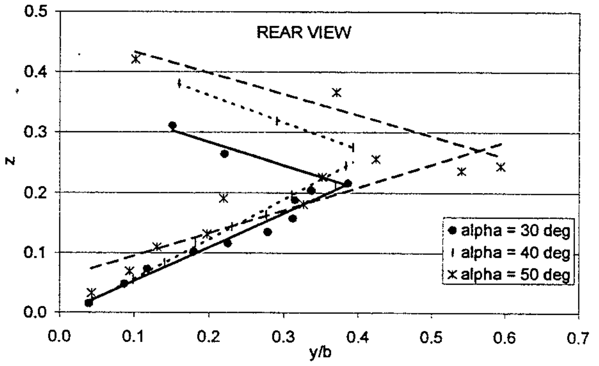
If the delta wing is viewed from the side, as in Figure



(a) Top View



(b) Side View



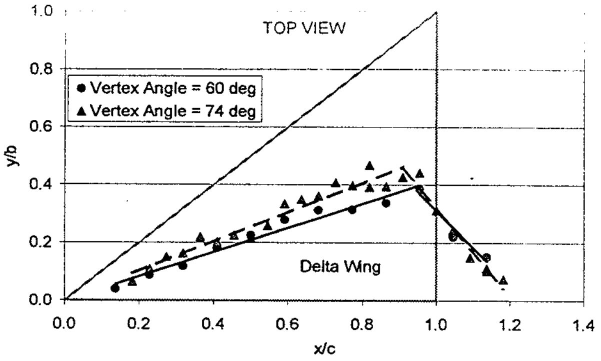
(c) Rear View

Figure 7: Vortex core position as a function of angle of attack; delta wing is outlined in gray.

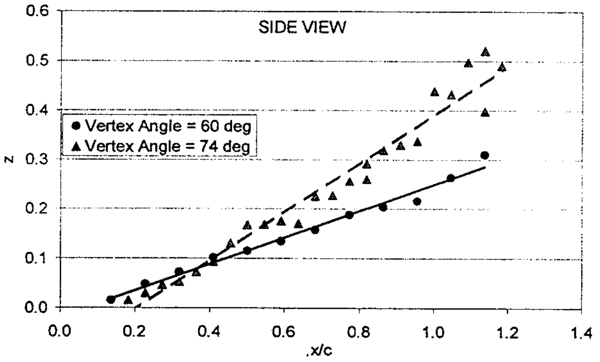
7b, the vortex cores diverge from the wing at a greater rate with increasing angle of attack, as expected. Viewed from behind in Figure 7c, the cores move upwards and outboard at about the same rate, but the breakdown occurs at increasingly delayed points. The points which trend back towards the centerline are in the breakdown region.

EFFECT OF VERTEX ANGLE

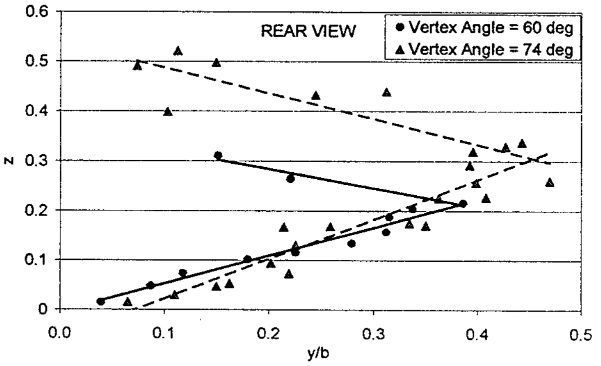
The delta wing vertex angle has a strong influence on the vortex position. To compare with the control case of $\Lambda = 60°$, a simulation was run for $\Lambda = 74°$, which corresponds to a more slender wing. Relative to the control case, the vortex core moved outboard in Figure 8a, but the breakdown point was nearly the same.



(a) Top View



(b) Side View



(c) Rear View

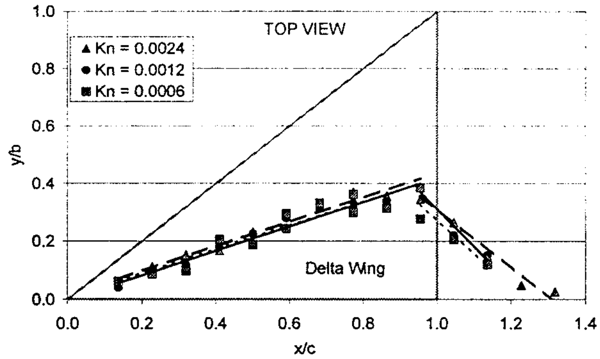
Figure 8: Vortex core position as a function of wing vertex angle; delta wing is outlined in gray.

For the same angle of attack, $\alpha = 30°$, the core diverged upwards at a rate 60% greater than the control case in Figure 8b. This difference is magnified in Figure 8c when viewed from behind the delta wing.

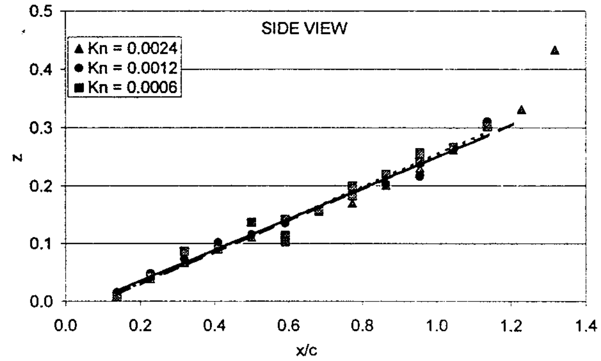
EFFECT OF KNUDSEN NUMBER

The Knudsen number of the simulation can have a significant effect on the qualitative and quantitative accuracy of the results. As Knudsen number directly relates to the closeness of a given simulation to the 'continuum' result, it is important that the effect of this parameter be characterised. Especially since current computers are not capable of simulating continuum conditions, it is useful to determine if a trend exists as Kn is varied. If a reasonable trend does exist, it may allow extrapolation to the continuum result.

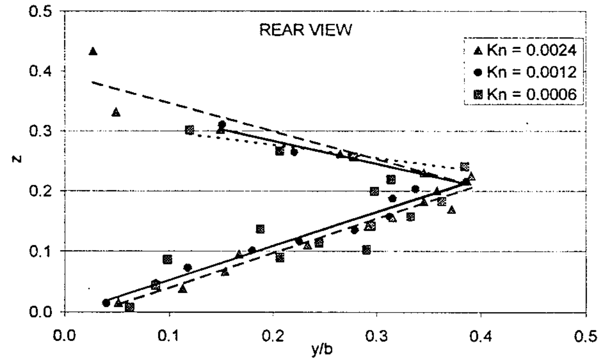
For the control case, Kn = 0.0012 based upon the wing chord. Variation in Knudsen number is achieved through variation in the number density. The same effect would be gained by changing the chord. The main difference in these techniques is that, although both also alter the Reynolds number, the change in number density also changes the static density, giving densities closer to sea level, continuum conditions. This is a desirable side-effect and the intent of this research, so variation in number density is employed.



(a) Top View



(b) Side View



(c) Rear View

Figure 9: Vortex core position as a function of Knudsen number; delta wing is outlined in gray.

Figure 9a-c indicate that for the given grid resolution and number of simulated molecules, the vortex core positions are nearly the same over the Knudsen number range. These results are consistent with a converged solution, referring to qualitative convergence in terms of vortex position. As discussed previously, the lift coefficient is less than experimental values by a factor of two, indicating that quantitative convergence has not yet been reached.

While the vortices exhibit expected positional trends, the vorticity and longevity are less than experimental results. Bird[17] showed this to be an important Knudsen number effect which he supported by one-dimensional vortical calculations.

EFFECT OF BOUNDARY CONDITIONS

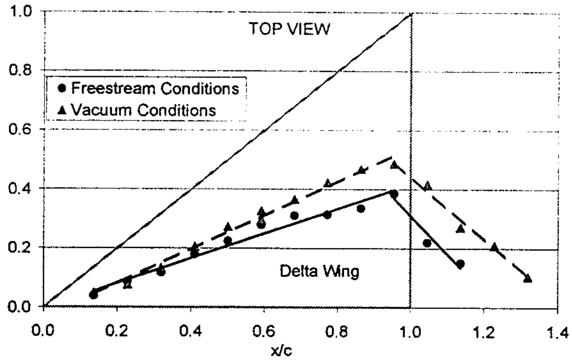
Previous research by Talbot-Stern[18] and Bird[17] revealed that the boundary position and nature can have significant influences on the flowfield.

Computational limitations restrict realistic enlargement of the control volume to simulate the change in boundary position. To obtain a minimal Knudsen number, the delta wing is sized as large as possible within the flowfield. An adverse result is the close proximity of the wing to the freestream boundaries. While the position of the boundary can simply be changed in the setup files, if this involves enlargening the flowfield the cell resolution and molecular density must be adjusted to maintain correct molecular interaction. This was beyond the scope of the available computational resources and is being addressed in ongoing research with more powerful computers.

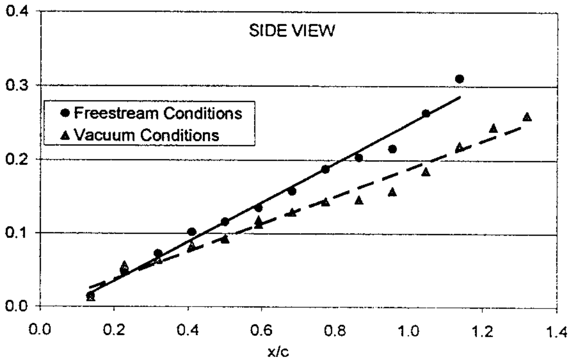
Without computational penalty, the effect of the boundary type was investigated. The control case employed freestream boundaries on all sides other than the plane of symmetry. The rear flowfield boundary was changed to vacuum to determine the effect of this boundary on the delta wing vortex formation. In the vacuum case, the influx is zero, while in the freestream case, the influx corresponds to the freestream flux normal and into the boundary. In the rarefied region behind the delta wing at angle of attack, the pressure and molecular flux will be less, most closely approximated by the vacuum condition.

There are two approaches to optimizing the boundary conditions to match the flow conditions more accurately. One is to extend the flowfield as detailed above, but this requires significant additional resources. The other is to iteratively modify the boundary flux conditions until a steady state condition is reached, at no resource cost. This study is currently under way at The University of Sydney. Both methods achieve the same result, but while the iterative boundary flux technique requires a more complex program, the result could provide the most accurate solution available for this case.

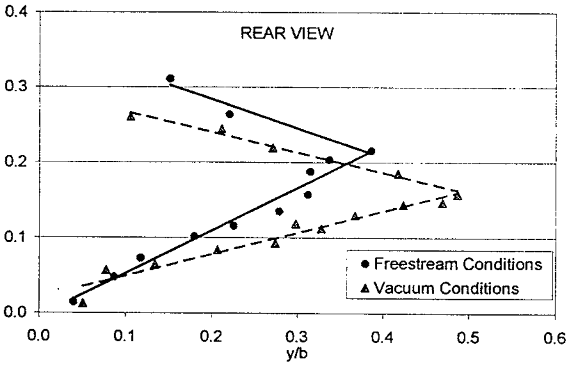
Figures 10a-c show that the rear boundary type has a significant influence on the vortex position and divergence. This hints at the need for a more detailed study of these parameters.



(a) Top View



(b) Side View



(c) Rear View

Figure 10: Vortex core position as a function of boundary type; delta wing is outlined in grey.

CONCLUSIONS

This research has established that the DSMC method is capable of simulating three-dimensional, subsonic, vortical delta wing flow. It can characterize the vortices from a qualitative standpoint, but is not yet capable of quantitative accuracy.

It was found that the vortex position changes as a function of angle of attack and wing vertex angle, as expected. The boundary conditions also have a strong effect upon the vortices.

Further research into improving the numerical accuracy and studies into the effect of the number of simulated molecules and cell resolution to ensure grid convergence is underway. The use of parallel processing is also being investigated to improve the overall resolution of the phenomenon.

REFERENCES

1. Monnerie, H and Werle, RM. "Study of Supersonic and Hypersonic Flow About a Slender Wing at an Angle of Attack." Hypersonic Boundary Layers and Flow Fields, AGARD CP-30, May 1968m pages 23.1 - 23.19
2. Hummel, D. "On the Vortex Formation over a Slender Wing at Lare Angles of Incidence." High Angle of Attack Aerodynamics, AGARD CP-247, 1987, pages 13.1 – 13.17.
3. Miller, DS and Wood, RM. "Lee-Side Flow over Delta Wings at Supersonic Speeds." NASA TP-2430, June 1985.
4. Stallings, RL and Lamb, M. "Wing-Alone Aerodynamic Characteristics for High Angles of Attack at Supersonic Speeds." NASA TP-1889, 1981.
5. Rizzetta, DP, and Shang, JS. "Numerical Simulation of Leading-Edge Vortex Flows." AIAA Journal, Vol 24, No 2, 1986, pages 237-245.
6. Buter, TA and Rizzetta, DP. "Steady Supersonic Navier-Stokes Solutions of a 75° Delta Wing." NASA CP-2416, Oct 1985.
7. Thomas, JL and Newsome, RW. "Navier-Stokes Computations of Leeside Flows Over Delta Wings." AIAA Paper 86-1949, May 1986.
8. Webster, WP and Shang, JS. "Thin-Layer Full Navier-Stokes Simulations over a Supersonic Delta Wing." AIAA Journal, Vol 29, No 9, Sep 1991, pages 1363 – 1369.
9. Thomas, JL, Taylor, SL and Anderson, WK. "Navier-Stokes Computations of Vortical Flows Over Low Aspect Ratio Wings." AIAA Paper 87-0207, Jan 1987.
10. McMillin, SN, Thomas, JL and Murman, EM.

"Euler and Navier-Stokes Solutions for the Leeside Flow Over Delta Wings at Supersonic Speeds." AIAA Paper 87-2270, Aug 1987.

11. Rizzi, A, Muller, B and Purcell, CJ. "Comparison of Euler and Navier-Stokes Soluations for Vortex Flow Over a Delta Wing." AIAA Paper 87-2347, Aug 1987.
12. Fujii, K and Schiff, LB. "Numerical Simulation of Vortical Flows over a Strake-Delta Wing." AIAA Journal, Vol 27, Sep 1989, pages 1153 – 1162.
13. Ekaterinaris, JA and Schiff, LB. "Vortical Flows over Delta Wings and Numerical Prediction of Vortex Breakdown." AIAA Paper 90-0102, Jan 1990.
14. Vadyak, J and Schuster, DM. "Navier-Stokes Simulation of Burst Vortex Flowfields for Fighter Aircraft at High Incidence." Journal of Aircraft, Vol 28, No 10, 1991, pages 638 – 645.
15. Agrawal, S, Barnett, RM, and Robinson, BA. "Numerical Investigation of Vortex Breakdown on a Delta Wing." AIAA Journal, Vol 30, No 3, March 1992.
16. Bird, GA. "Molecular Gas Dynamics and the Direct Simulation of Gas Flows." Clarendon Press, Oxford, 1994.
17. Bird, GA. "Knudsen and Mach number Effects on the Development of Wake Instabilities." AIAA Paper 98-0785, 1998.
18. Talbot-Stern, JL. "Direct Simulation (Monte Carlo) of Two Dimensional Vortex Streets." AIAA Paper 98-2761, 1998.
19. O'Neil, PJ, Roos, FW, Kegelman, JT, Barnett, RM and Hawk, JD. "Investigation of Flow Characteristics of a Developed Vortex." Final Report, NADC-89114-60, May 1989.