Study
of the
Aerodynamics
of a
Small UAV
using
AVL Software

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April 24, 2006

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Introduction

During the Winter '06 semester I studied the aerodynamics of a small flying-wing type UAV using the Athena Vortex Lattice (AVL) software developed by Prof. Mark Drela at MIT. AVL is an extended vortex-lattice model program that claims it is useful for aerodynamic analysis, trim calculations, dynamic stability analysis, and aircraft configuration development. In the course of my study, I constructed the geometry description file as used by AVL for the UAV model, and used the software to calculate various aerodynamic properties. I also compared these results to those obtained from the LiftLine code for Matlab, to be taken as a standard.

Aerodynamic Data

Two of the most important calculations needed for an airplane are the coefficients of lift and drag, which put limitations on the airplane's aerodynamic performance, thereby affecting also the power and thrust requirements.

According to lifting-line theory, the slope of an airfoil's lift curve (CLα) should be 2π per radian, or 0.110 per degree angle of attack. Adding thickness and camber effects, the airfoil (a modified MH45) used by the UAV has a lift curve slope of 0.126, as calculated by XFoil. Due to wing tip effects, a 3-dimensional wing actually produces less lift. As can be seen in Figure 1 below, the lift curve slope is actually 0.073 by LiftLine, or about 0.053 by AVL. Clearly, there is a slight difference between the two calculations. However, they both find that the zero lift angle is very close to -1°.
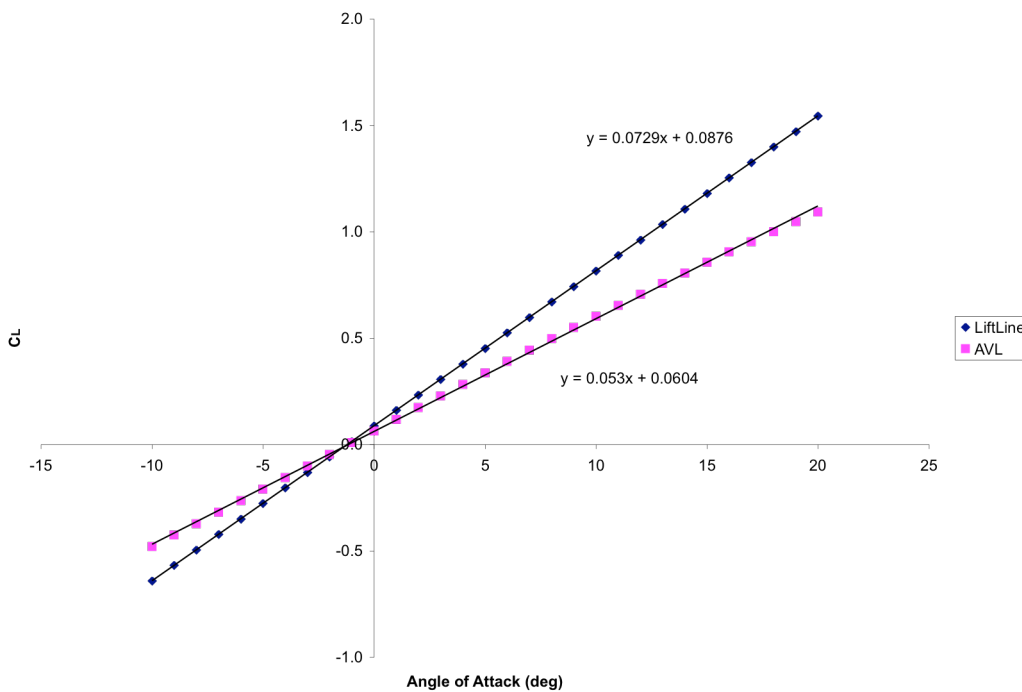
Figure 1: Comparison of lift curves between LiftLine and AVL.
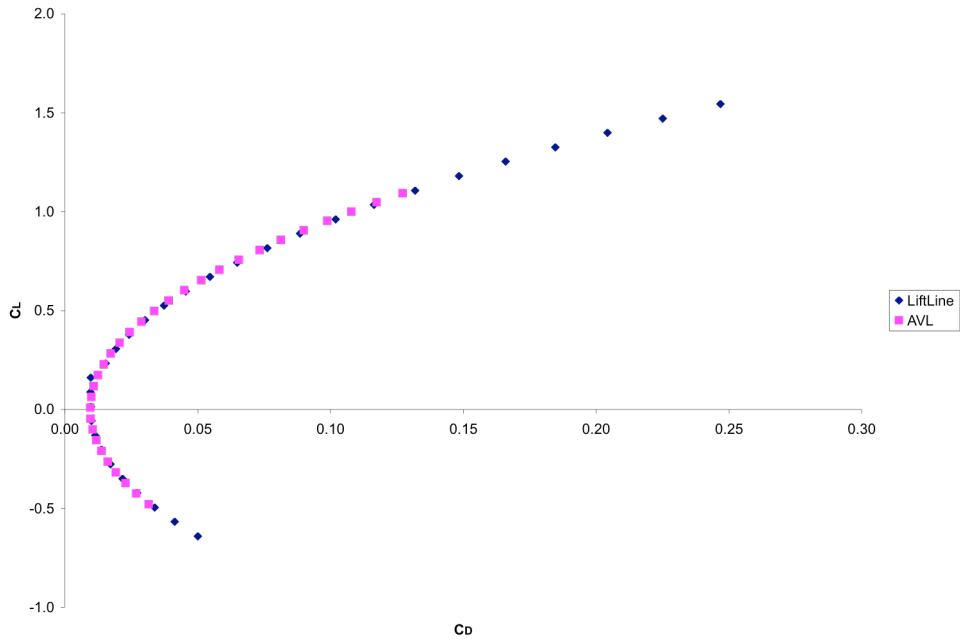
Figure 2: Comparison of drag polars between LiftLine and AVL.

Figure 2 shows the drag polars as calculated by LiftLine and AVL. Both codes only calculate inviscid flow, so the actual value for CD is the sum of CD_0 found by some other method, and the value for CD_i calculated by the code. For this case, I used the value of CD_0 from the airfoil, found using XFoil to be 0.0095. Although the data points from the LiftLine drag polar are spread out more than those from AVL, that is because of the steeper slope of the lift curve. The drag polars lie right on top of each other, showing very close agreement in calculation.

Figure 3: Lift curve comparison at yaw angles 0°, 5°, and 10°.

Figure 4: Drag polar comparison for yaw angles 0°, 5°, and 10°.

An advantage held by AVL is that it can run cases at various yaw angles and roll rates, in addition to the angles of attack realizable with LiftLine. I used AVL to find the lift c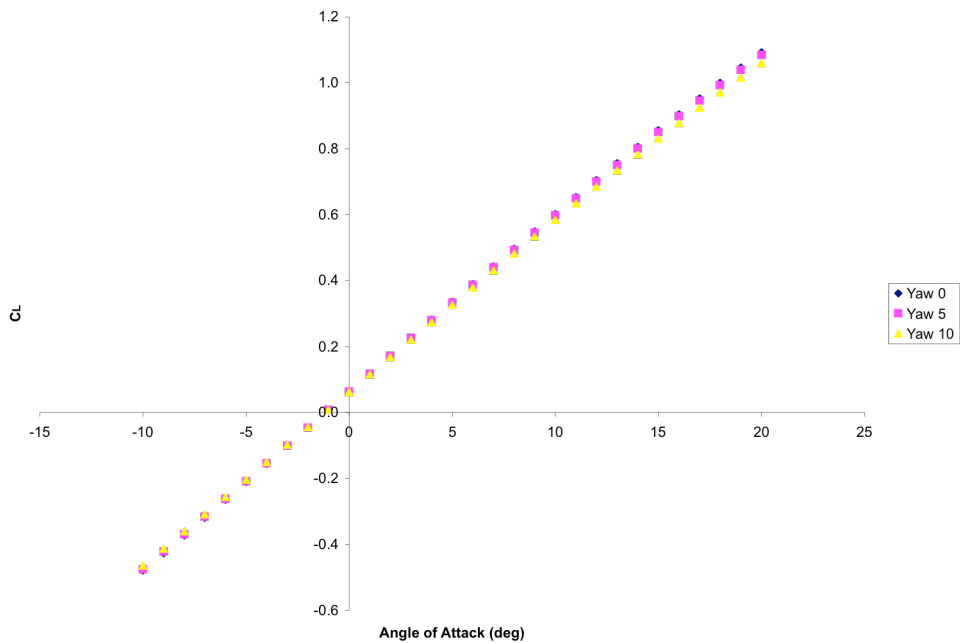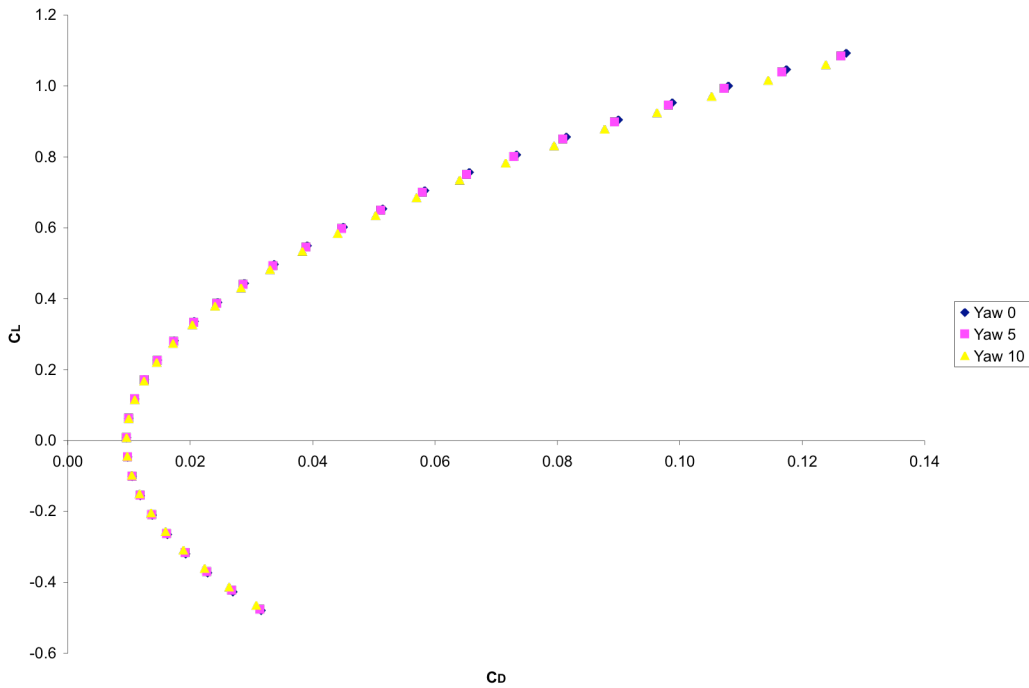urves and drag polars at yaw angles of 0°, 5°, and 10°. As can be seen from figures 3-4, the yaw has a slight, but not significant, effect on the coefficients of lift and drag.

AVL is also capable of calculating stability derivatives for the aircraft. It calculates the derivatives of the coefficients of lift and side force, and of the three moments, with respect to angle of attack, sideslip angle, and the three roll rates. At 0° for both angle of attack and yaw, AVL calculate the values in Table 1 for the stability derivatives of the UAV. According to lifting line theory, the value for CL_α should be 2π. As can be seen, AVL calculates it to be about half that. Converting CL_α from rad^{-1} to deg^{-1} gives 0.055.

	α	β	Roll p'	Pitch q'	Yaw r'
CL	3.143	1E-6	8E-6	4.282	-1E-6
CY	0.000	-0.0107	0.0296	-1E-6	0.00171
Roll Moment	-4E-6	-0.0397	-0.270	-7E-6	0.0382
Pitch Moment	-0.500	0.000	-3E-6	-1.671	0.000
Yaw Moment	0.000	0.000115	-0.0144	0.000	-0.00039

Table 1: Stability derivatives at 0° angle of attack, 0° yaw.

I repeated these calculations for the same range of angle of attack as in the above graphs to find how CL_α changes with angle of attack, as shown in Figure 5 below.
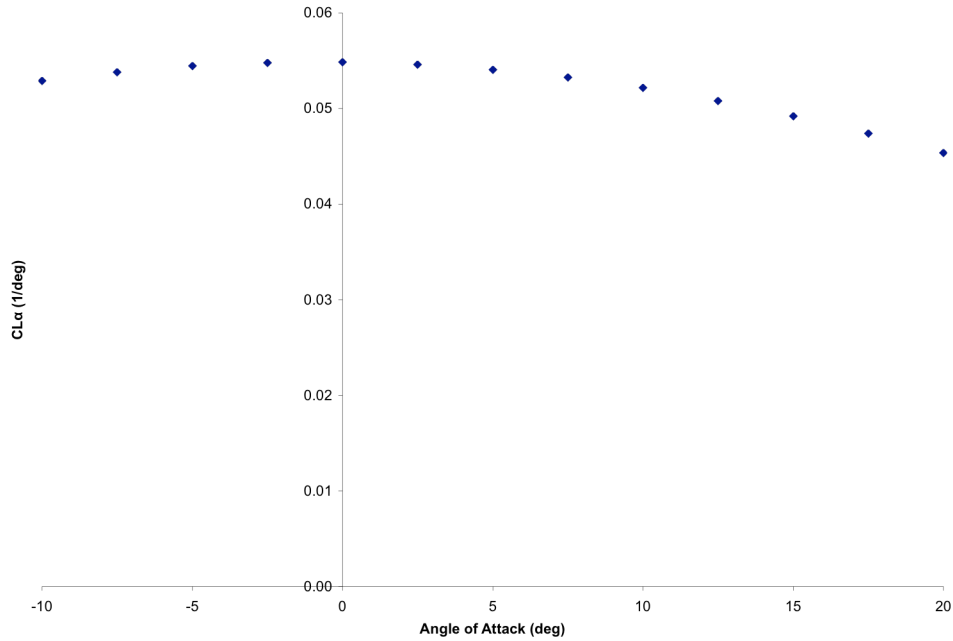
Figure 5: CL$_\alpha$ (in deg^{-1}) against angle of attack (deg).

Flight Assessment

Using the data found above with AVL, it is possible to assess the flight requirements for this UAV. One important type of information that can be found from the above data is the power requirement. To maintain steady level flight, the lift must balance the weight, and the thrust must balance the drag. The weight is constant for an electric vehicle, so the lift must remain the same, but the drag is dependent on the speed and the angle of attack.

For a given speed, the necessary coefficient of lift to maintain a steady level flight is given by Equation 1:

$$C_L = \frac{W}{\frac{1}{2}\rho v^2 S} \qquad\qquad [1]$$

where W is the weight of the airctaft, ρ is the air density, v is the speed, and S is the surface area. The drag coefficient can then be found using Equation 2:

$$C_D = C_{D0} + KC_L{}^2 \qquad\qquad [2]$$

where C_{D0} is the parasite drag coefficient, and K is calculated from the drag polar. The thrust is then equal to the drag, as shown in Equation 3, and the power is equal to the thrust times the speed, shown in Equation 4:

4

$$T = D = \frac{1}{2}\rho v^2 S C_D \qquad\qquad\qquad\qquad [3]$$

$$P = Tv \qquad\qquad\qquad\qquad [4]$$

Using these equations and a mass of 1.2 kg, I found the minimum thrust to be 0.725 N at 20 m/s, 5° angle of attack. At this condition, the power required is 14.5 W. The minimum power, on the other hand, is 12.7 W at 15 m/s, 9° angle of attack, and requiring 0.85 N of thrust.

Conclusions

AVL can be a very useful tool for quickly evaluating an airplane configuration scheme. It only gives an inviscid approximation, but the data are easy and quick to calculate, and close in value to wind tunnel tests and full CFD calculations such as those from Fluent. Consequently, a design can be evaluated initially using AVL, and then fine-tuned with a full-blown CFD code before being wind tunnel tested to ensure accuracy.

In this case, the coefficients of lift and drag indicate fairly low thrust and power requirements. The stability derivatives indicate that the body design is slightly unstable in yaw (since CYB is positive), which can be corrected for with the addition of vertical stabilizers.

Appendix A: Coefficient Data

Alpha	CL	CD	CY	Cl	Cm	Cn	CL/CD
-10.00	-0.48	0.03	0.00	0.00	0.08	0.00	-15.17
-9.00	-0.43	0.03	0.00	0.00	0.07	0.00	-15.81
-8.00	-0.37	0.02	0.00	0.00	0.07	0.00	-16.32
-7.00	-0.32	0.02	0.00	0.00	0.06	0.00	-16.55
-6.00	-0.26	0.02	0.00	0.00	0.05	0.00	-16.30
-5.00	-0.21	0.01	0.00	0.00	0.04	0.00	-15.29
-4.00	-0.16	0.01	0.00	0.00	0.03	0.00	-13.15
-3.00	-0.10	0.01	0.00	0.00	0.02	0.00	-9.63
-2.00	-0.05	0.01	0.00	0.00	0.01	0.00	-4.77
-1.00	0.01	0.01	0.00	0.00	0.01	0.00	0.87
0.00	0.06	0.01	0.00	0.00	0.00	0.00	6.33
1.00	0.12	0.01	0.00	0.00	-0.01	0.00	10.77
2.00	0.17	0.01	0.00	0.00	-0.02	0.00	13.80
3.00	0.23	0.01	0.00	0.00	-0.03	0.00	15.51
4.00	0.28	0.02	0.00	0.00	-0.04	0.00	16.23
5.00	0.34	0.02	0.00	0.00	-0.05	0.00	16.29
6.00	0.39	0.02	0.00	0.00	-0.05	0.00	15.95
7.00	0.44	0.03	0.00	0.00	-0.06	0.00	15.39
8.00	0.50	0.03	0.00	0.00	-0.07	0.00	14.74
9.00	0.55	0.04	0.00	0.00	-0.08	0.00	14.05
10.00	0.60	0.05	0.00	0.00	-0.09	0.00	13.37
11.00	0.65	0.05	0.00	0.00	-0.10	0.00	12.72
12.00	0.71	0.06	0.00	0.00	-0.10	0.00	12.10
13.00	0.76	0.07	0.00	0.00	-0.11	0.00	11.53
14.00	0.81	0.07	0.00	0.00	-0.12	0.00	11.00
15.00	0.86	0.08	0.00	0.00	-0.13	0.00	10.51
16.00	0.90	0.09	0.00	0.00	-0.14	0.00	10.06
17.00	0.95	0.10	0.00	0.00	-0.14	0.00	9.65
18.00	1.00	0.11	0.00	0.00	-0.15	0.00	9.27
19.00	1.05	0.12	0.00	0.00	-0.16	0.00	8.92
20.00	1.09	0.13	0.00	0.00	-0.16	0.00	8.59

Table A.1: Coefficients at 0° yaw.

Appendix B: Data File for UAV Case Study (Body Geometry)

The input to AVL consists of a geometry file and optional run case settings and mass definition files. The geometry file has a header which defines the aircraft name and a few parameters, such as whether the airplane should be automatically created symmetrically about one or more axes, constants used to calculate aerodynamic coefficients, and a reference location about which to take moments and rotation rates.

Following this are sections for wing-like structures and fuselage-like structures. Sections for wing-like structures are indicated by the keyword *SURFACE*. Then comes the name of the surface, and the number and spacing of vortices in both the chordwise and spanwise directions. An optional keyword *YDUPLICATE* tells AVL to make a mirror image of the geometry.

Following this SURFACE header, come multiple *SECTIONs*. Each of these defines an airfoil section of the wing. It gives the leading edge in 3D coordinates, the chord length, twist angle, and optional additional vortex lattice sizing. The description of the actual airfoil section can be given as a NACA airfoil, raw coordinates embedded in the geometry file, or the name of a file containing the coordinates, as output by XFoil.

The input file for the UAV (a file named "uav.avl", given below) produces the geometry plot in Figure A.1, which shows the chord at each defined section, as well as the vortex lattice.
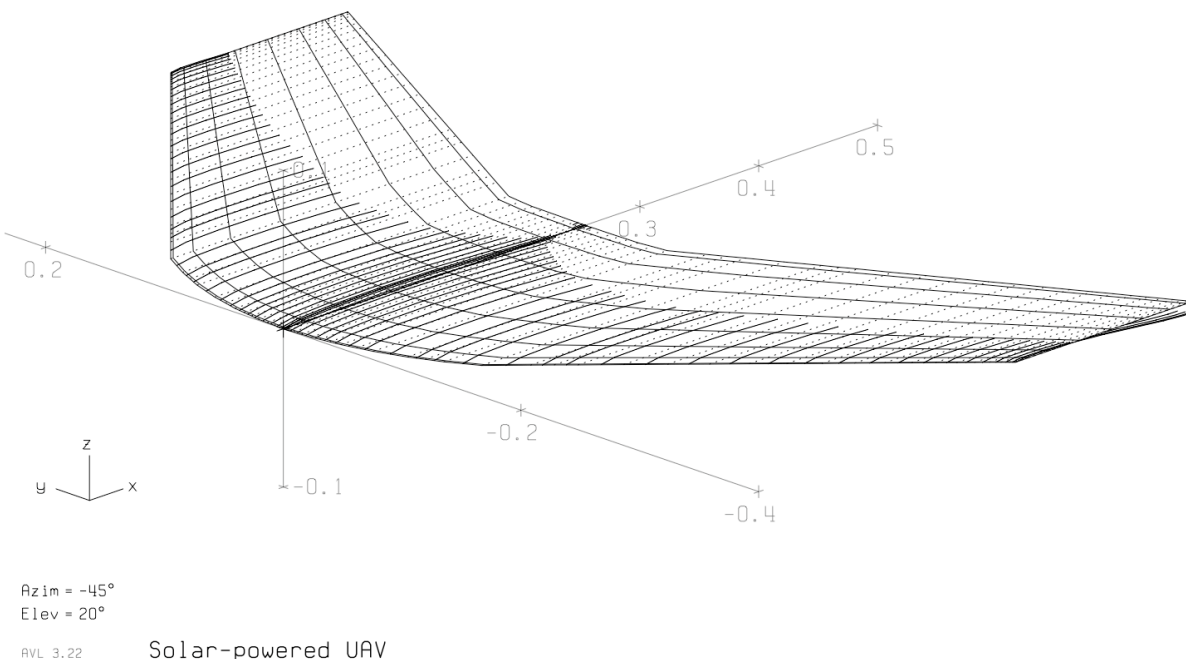

Figure B.1: Geometry plot of UAV.

Solar-powered UAV
#Mach
 0.0
#IYsym   IZsym   Zsym
 0   0   0.0
#Sref   Cref   Bref
0.156619 0.711200   0.220219
#Xref   Yref   Zref
0.50   0.0   0.0
#
#
#===
SURFACE
Wing
#Nchordwise Cspace   Nspanwise   Sspace
8   1.0   34   1.0
#
YDUPLICATE
0.0
#
ANGLE
0
#---------------------
SECTION
#Xle   Yle   Zle   Chord Ainc   [Nspan Sspace]
-0.000000   0.000000   0.000000   0.254000   0.000000
AFILE
MH45MOD.dat
#---------------------
SECTION
#Xle   Yle   Zle   Chord Ainc   [Nspan Sspace]
0.000983 0.022328   0.000205   0.253020   0.174645
AFILE
MH45MOD.dat
#---------------------
SECTION
#Xle   Yle   Zle   Chord Ainc   [Nspan Sspace]
0.003941 0.044568   0.000410   0.250060   0.348603
AFILE
MH45MOD.dat
#---------------------
SECTION
#Xle   Yle   Zle   Chord Ainc   [Nspan Sspace]
0.008896 0.066633   0.000613   0.247430   0.521191
AFILE
MH45MOD.dat
#---------------------
SECTION
#Xle   Yle   Zle   Chord Ainc   [Nspan Sspace]
0.015892 0.088434   0.000814   0.252030   0.691714
AFILE
MH45MOD.dat
#---------------------
SECTION

```
#Xle    Yle     Zle     Chord  Ainc    [Nspan Sspace]
0.025000  0.109890  0.001011  0.254330  0.859539
AFILE
MH45MOD.dat
#---------------------
SECTION
#Xle    Yle     Zle     Chord  Ainc    [Nspan Sspace]
0.036087  0.130910  0.001204  0.254410  1.023953
AFILE
MH45MOD.dat
#---------------------
SECTION
#Xle    Yle     Zle     Chord  Ainc    [Nspan Sspace]
0.056589  0.151410  0.001393  0.244810  1.184301
AFILE
MH45MOD.dat
#---------------------
SECTION
#Xle    Yle     Zle     Chord  Ainc    [Nspan Sspace]
0.076494  0.171310  0.001576  0.235490  1.339955
AFILE
MH45MOD.dat
CONTROL
aileron   1.000000 0.300000 0. 0. 0. -1.0
CONTROL
elevator  1.000000 0.300000 0. 0. 0. 1.0
#---------------------
SECTION
#Xle    Yle     Zle     Chord  Ainc    [Nspan Sspace]
0.095722  0.190540  0.001753  0.226490  1.490368
AFILE
MH45MOD.dat
CONTROL
aileron   1.000000 0.300000 0. 0. 0. -1.0
CONTROL
elevator  1.000000 0.300000 0. 0. 0. 1.0
#---------------------
SECTION
#Xle    Yle     Zle     Chord  Ainc    [Nspan Sspace]
0.114200  0.209020  0.001923  0.217840  1.634915
AFILE
MH45MOD.dat
CONTROL
aileron   1.000000 0.300000 0. 0. 0. -1.0
CONTROL
elevator  1.000000 0.300000 0. 0. 0. 1.0
#---------------------
SECTION
#Xle    Yle     Zle     Chord  Ainc    [Nspan Sspace]
0.131850  0.226670  0.002085  0.209570  1.772970
AFILE
MH45MOD.dat
CONTROL
aileron   1.000000 0.300000 0. 0. 0. -1.0
```

CONTROL
elevator 1.000000 0.300000 0. 0. 0. 1.0
#---------------------
SECTION
#Xle   Yle   Zle   Chord Ainc   [Nspan Sspace]
0.148610   0.243420   0.002239   0.201720   1.903985
AFILE
MH45MOD.dat
CONTROL
aileron   1.000000 0.300000 0. 0. 0. -1.0
CONTROL
elevator 1.000000 0.300000 0. 0. 0. 1.0
#---------------------
SECTION
#Xle   Yle   Zle   Chord Ainc   [Nspan Sspace]
0.164400   0.259220   0.002385   0.194330   2.027570
AFILE
MH45MOD.dat
CONTROL
aileron   1.000000 0.300000 0. 0. 0. -1.0
CONTROL
elevator 1.000000 0.300000 0. 0. 0. 1.0
#---------------------
SECTION
#Xle   Yle   Zle   Chord Ainc   [Nspan Sspace]
0.179180   0.273990   0.002521   0.187410   2.143098
AFILE
MH45MOD.dat
CONTROL
aileron   1.000000 0.300000 0. 0. 0. -1.0
CONTROL
elevator 1.000000 0.300000 0. 0. 0. 1.0
#---------------------
SECTION
#Xle   Yle   Zle   Chord Ainc   [Nspan Sspace]
0.192870   0.287690   0.002647   0.181000   2.250257
AFILE
MH45MOD.dat
CONTROL
aileron   1.000000 0.300000 0. 0. 0. -1.0
CONTROL
elevator 1.000000 0.300000 0. 0. 0. 1.0
#---------------------
SECTION
#Xle   Yle   Zle   Chord Ainc   [Nspan Sspace]
0.205420   0.300240   0.002762   0.175120   2.348421
AFILE
MH45MOD.dat
CONTROL
aileron   1.000000 0.300000 0. 0. 0. -1.0
CONTROL
elevator 1.000000 0.300000 0. 0. 0. 1.0
#---------------------
SECTION

```
#Xle    Yle     Zle     Chord  Ainc    [Nspan Sspace]
0.216800   0.311610   0.002867   0.169790   2.437355
AFILE
MH45MOD.dat
CONTROL
aileron   1.000000 0.300000 0. 0. 0. -1.0
CONTROL
elevator  1.000000 0.300000 0. 0. 0. 1.0
#---------------------
SECTION
#Xle    Yle     Zle     Chord  Ainc    [Nspan Sspace]
0.226940   0.321760   0.002960   0.165040   2.516746
AFILE
MH45MOD.dat
CONTROL
aileron   1.000000 0.300000 0. 0. 0. -1.0
CONTROL
elevator  1.000000 0.300000 0. 0. 0. 1.0
#---------------------
SECTION
#Xle    Yle     Zle     Chord  Ainc    [Nspan Sspace]
0.235810   0.330630   0.003042   0.160890   2.586126
AFILE
MH45MOD.dat
CONTROL
aileron   1.000000 0.300000 0. 0. 0. -1.0
CONTROL
elevator  1.000000 0.300000 0. 0. 0. 1.0
#---------------------
SECTION
#Xle    Yle     Zle     Chord  Ainc    [Nspan Sspace]
0.243380   0.338200   0.003111   0.157340   2.645337
AFILE
MH45MOD.dat
CONTROL
aileron   1.000000 0.300000 0. 0. 0. -1.0
CONTROL
elevator  1.000000 0.300000 0. 0. 0. 1.0
#---------------------
SECTION
#Xle    Yle     Zle     Chord  Ainc    [Nspan Sspace]
0.249610   0.344430   0.003169   0.154420   2.694067
AFILE
MH45MOD.dat
CONTROL
aileron   1.000000 0.300000 0. 0. 0. -1.0
CONTROL
elevator  1.000000 0.300000 0. 0. 0. 1.0
#---------------------
SECTION
#Xle    Yle     Zle     Chord  Ainc    [Nspan Sspace]
0.254480   0.349300   0.003214   0.152140   2.732159
AFILE
MH45MOD.dat
```

CONTROL
aileron   1.000000 0.300000 0. 0. 0. -1.0
CONTROL
elevator 1.000000 0.300000 0. 0. 0. 1.0
#---------------------
SECTION
#Xle   Yle   Zle   Chord Ainc   [Nspan Sspace]
0.257980   0.352800   0.003246   0.150510   2.759535
AFILE
MH45MOD.dat
CONTROL
aileron   1.000000 0.300000 0. 0. 0. -1.0
CONTROL
elevator 1.000000 0.300000 0. 0. 0. 1.0
#---------------------
SECTION
#Xle   Yle   Zle   Chord Ainc   [Nspan Sspace]
0.260080   0.354900   0.003265   0.149520   2.775961
AFILE
MH45MOD.dat
CONTROL
aileron   1.000000 0.300000 0. 0. 0. -1.0
CONTROL
elevator 1.000000 0.300000 0. 0. 0. 1.0
#---------------------
SECTION
#Xle   Yle   Zle   Chord Ainc   [Nspan Sspace]
0.260780   0.355600   0.003272   0.149190   2.781436
AFILE
MH45MOD.dat
CONTROL
aileron   1.000000 0.300000 0. 0. 0. -1.0
CONTROL
elevator 1.000000 0.300000 0. 0. 0. 1.0

Appendix C: Data File for UAV Case Study (Run File)

The run case file contains important parameters such as the parasite drag coefficient, air speed, gravitation acceleration, center of gravity location, and masses and moments. If this file is not present, the values are assumed to be either 0 or 1, depending on their use. For the UAV study, I used the file as follows named "uav.run":

```
Run case  1:  Default

alpha        -> alpha      =  0.00000
beta         -> beta       =  0.00000
pb/2V        -> pb/2V      =  0.00000
qc/2V        -> qc/2V      =  0.00000
rb/2V        -> rb/2V      =  0.00000
aileron      -> aileron    =  0.00000
elevator     -> elevator   =  0.00000

alpha     =  0.00000
beta      =  0.00000
pb/2V     =  0.00000
qc/2V     =  0.00000
rb/2V     =  0.00000
CL        =  0.00000
CDo       =  0.00950
bank      =  0.00000
elevation =  0.00000
heading   =  0.00000
Mach      =  0.00000
velocity  =  15.0000
density   =  1.22500
grav.acc. =  9.81000
turn_rad. =  0.00000
load_fac. =  0.00000
X_cg      =  0.10000
Y_cg      =  0.00000
Z_cg      =  0.00000
mass      =  1.00000
Ixx       =  1.00000
Iyy       =  1.00000
Izz       =  1.00000
Ixy       =  0.00000
Iyz       =  0.00000
Izx       =  0.00000
visc CL_a =  0.00000
visc CL_u =  0.00000
visc CM_a =  0.00000
visc CM_u =  0.00000
```

Appendix D: AVL Operation

Once you have constructed the appropriate *.avl* geometry file, you main commence operation of the AVL software. It is a command-line driven too similar to XFoil, and has executable binaries available for Windows and Linux, and easily compiled for Mac OS X. It is currently installed on the Linux side of CAEN lab PC's.

AVL can be opened directly, or passed a *.avl* file to open. If you do not pass the *.avl* file, you can load it by using the *LOAD* command from the main menu. Assuming the geometry file is well-defined, it will be read in and the geometry stored in memory.

Once the geometry file has been loaded, you will want to enter the *OPER* menu. Here you can set parameters such as the angle of attack, sideslip angle, roll rates, control surface deflections, and various other parameters. For the UAV case study, I primarily used the *A* (angle of attack, alpha) and *B* (yaw angle, beta) commands. You can constrain these values to match other parameters, e.g., set the angle of attack such that the coefficient of lift is zero, or set the value directly.

Once you have set the variables and parameters appropriately, use the *X* command to execute the run case, and compute the results. Once it has computed the results of the vortex lattice analysis, AVL prints out the total forces and moments in the body-fixed and stability axes. The stability derivatives can be found by entering the *ST* command, which prints derivatives of the coefficients of lift, side force, and all three moments with respect to angle of attack, sideslip angle, and the three roll rates. It also calculates the neutral point.

For example, to calculate the lift curve, one could enter "A A -15" to set the angle of attack to -15°, then *X* to compute, and enter the value displayed for CLtot and/or CDtot or any of the other desired data into a text file or spread sheet. Then repeat this for as many angles as desired. One thing to keep in mind is that since AVL does not employ a viscous model for air, separation and stall effects will never occur. This can be repeated also for different sideslip angles by using "B B 10" to set beta to 10°, or whatever the desired sideslip angle is. In each case, once AVL has executed the run and printed the results, the stability derivatives for those parameters may be found by executing the *ST* command.

Appendix E: AVL Errors & Limitations

There are a few problems I encountered while using AVL that cause it to crash, sometimes giving a useful error message, other times without.

*** Cannot adjust spanwise spacing at section <N>, on surface Wing
 *** Insufficient number of spanwise vortices to work with

In the *SURFACE* section of the geometry file, the third number after the name gives the number of spanwise vortices (*Nspanwise)* to distribute across the wing. If there are too many sections given, AVL gives up and crashes with this error message. I experimentally determined that *Nspanwise* must be about 1.26 times the number of sections.

* MAKESURF: Array overflow. Increase KSMAX to <N>

This occurs if *Nspanwise* is too high. This is a value that is hard-coded in the Fortran source files. You can recompile with this constant changed to allow for more vortices. There is a similar error when AVL attempts to build the duplicated wing surface:

SDUPL: Strip array overflow. Increase NSMAX.

This is another constant that must be modified in the Fortran source and recompiled to allow for a greater number of vortices.

If AVL crashes without an error code while loading a geometry file, there is probably something amiss in the file. This is generally due to a misformatted or missing number somewhere.