Optimized Flight Efficiency with FEM Analysis

New Mexico Supercomputing Challenge

Final Report

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Team 93

Sandia Preparatory School

Author

Garrett Lewis

Sponsor

Neil McBeth

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Executive Summary

With the massive growth of air transport in the past century, it has become ever more important to establish effective methods of drag reduction and energy conservation into new aircraft. This project has sought to identify a novel and efficient method to accommodate these needs through the application of the Kutta condition describing airflow about a body and implement a test mechanism for this method in wind tunnel conditions for verification. Using Elmer, a finite element solver, a model was computationally simulated in controlled airflow to determine drag levels against a control figure representing a solitary rectangular wing. The simulation then sought to optimize this model independently of the programmer and return the top design found.

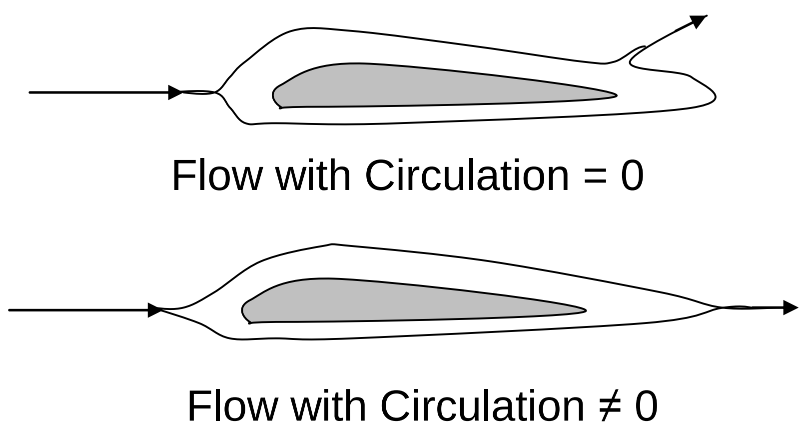
The optimized design was obtained by expanding on the forces experienced under the Kutta condition and applying these calculations on a wing. Integration across this airfoil then provided finite values for the net forces acting parallel to the wing and correspondingly offered insight into the production of wing vortices.

Expansion of methods developed to verify the Kutta condition in two dimensions was used to establish the magnitude of forces acting on the airfoil to in turn estimate flight performance. The data was stored for comparison against an alternative wing layout to determine the design of yet a third wing that incorporates the information of the previous two to effect a reduction in induced drag and an increase in lift production. The process was designed to repeat itself using the most recent pair of wing designs to establish successively improved conditions. This program then continued to iterate until improvements became negligible on successive airfoils, at which time the final result was recorded as the ideal airfoil under the given flight conditions.

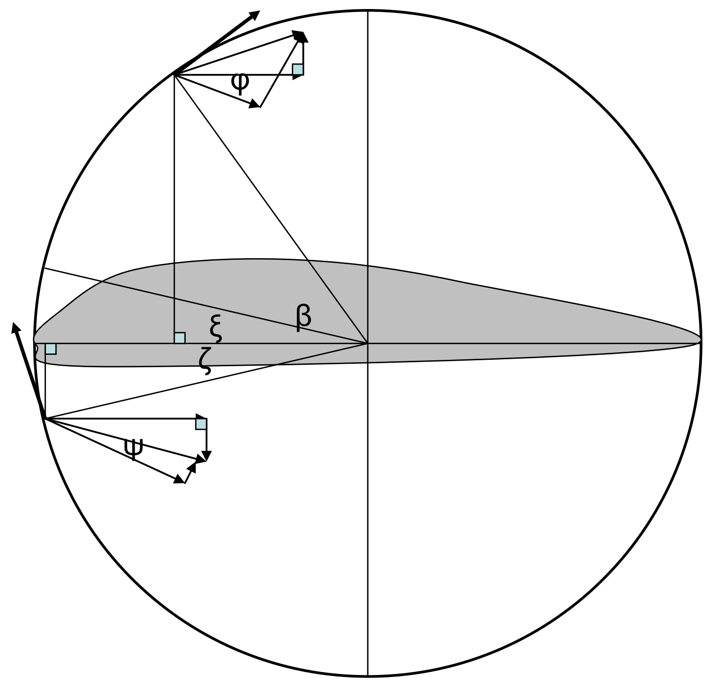
Introduction

There are in existence almost as many explanations of the sources of lift production as there are airfoils in the NACA archives. These methods range from the most common, Bernoulli's principle, to rather obscure vorticy-generated effects at wingtips that are obscured with forms of drag, with a similar range of reliability and accuracy further rifting the options.

One of the better-established explanations for the behavior is achieved through the Circulation described in the Kutta-Joukowski Theorem, named for its co-creators, which dictates that in a free-flowing stream with no circulation, that is, no rotational characteristics, there will be a constant pressure along any plane perpendicular to the flow and thus no lift; however, if a rotation is introduced to the flow, there will be produced a corresponding force that is the product of the fluid's density (ρ), the free-stream velocity (V), and the circulation parameter (Γ). In the case of airfoils, this force is generally considered to be lift.



For most airfoils, this concept might be readily accepted, as it seems to support the ever-popular Bernoulli principle by creating a rapidly moving zone above the wing and a slower area on the underside with circulation centered on the airfoil such that the air on the leading edge is moving upward. Continuing to follow this flow as it circles the wing (which remains in constant motion through the fluid), accelerating the motion above as it moves to the trailing edge where downwash, used in Newtonian explanations of lift, is released. The final leg back to the leading edge applies a degrading force against rearward motion that slows the flow and further exasperates the velocity and corresponding pressure gradients across the foil.

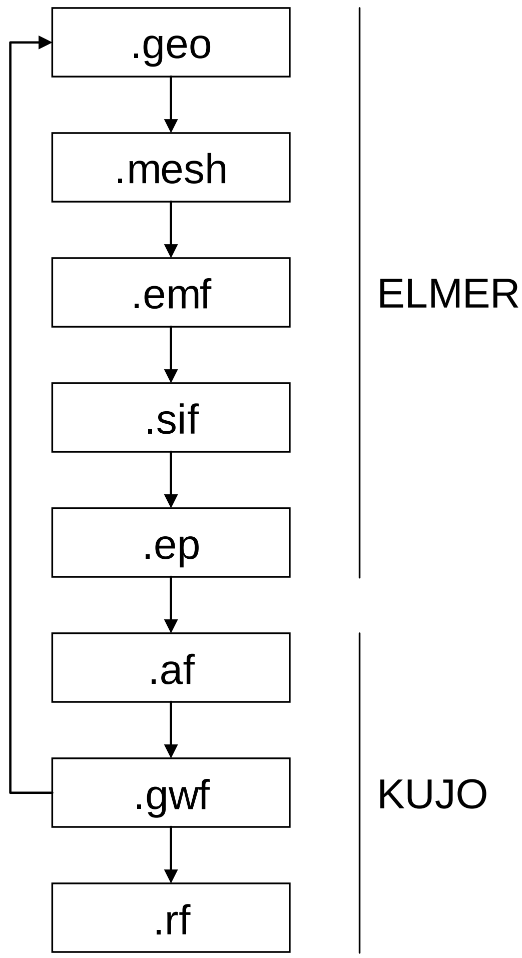


Integrating pressure about the closed interval over the wing creates a final vector force that impels the object perpendicularly to the flow stream in the same plane as the circulation. In the case of an airplane in standard flight, this will be vertically upwards.

Of course, this singular force does not account for effects of parasite drag, trailing vortices, *et cetera*. These forces also play on the wing, disguising the patterns created solely by the circulation. However, this does not mar wholly the significance of the primary effect of lift production as predicted by the theorem's devisors.

There is some variation, though, as the wing experiences the increased drag that is associated with increased lift. The drag then affects the overall performance of the airfoil under a given set of conditions as it holds the potential to grow beyond acceptable levels as thicker airfoils increase speed, preventing increased aircraft performance. Moreover, as the growth of drag is exponential with speed, this occurs very quickly.

Computational Model



An application, dubbed KUJO, has been developed with the goal of studying this phenomenon to discern the shape of the most effective airfoil under prescribed conditions. The program has been established to function with ELMER, an existing finite element solver to automatically estimate airfoil performance in the given scenario and determine how to adjust that airfoil to effectively ameliorate the imperfections in the lift-to-drag ratio over several iterations.

Initially writing a basic geometry file to input into ELMER, KUJO is designed to initiate the process leading up to a finite element solution for the airfoil in theoretical test-bed conditions. KUJO also writes the model file and solver input file that are compiled after meshing the geometry to provide the framework for a simple FEM solution via the ELMER solver. While each of these files with the exception of the geometry could also be manually produced in ELMER Front, KUJO uses the opportunity to establish an automated system that removes responsibility from the designer and allows the computer to make independent, ad consistent decisions. This then provides the data to analyze airfoil performance in the latter half of KUJO's application.

KUJO has been designed to identify features in the airflow presented by the finite Element solution to estimate the lift-to-drag ratio of the airfoil. Using data on fluid velocity in the vicinity of the airfoil, the program approximates the airfoil performance and produced an analysis file recording this data for reference on future iterations. This data is then used to adjust airfoil parameters relative to the original and produce an improved geometry for successive study. A brief version of the analytical results is stored in a result file that remains outside the iterative loop and is updated rather than replaced over time.

The program uses the new-found data of the geometry write file to determine the appropriate values for the following iteration. This produces, ideally, a chain of successive airfoils that consistently improve performance over time and removes the less-effective designs from the pool as they are passed over. This continues until performance increases remain consistently below levels prescribed by the user as negligible, at which point the loop is broken and a final design rendered in the solver. Furthermore, the expanded data related by this airfoil is recorded in expanded version within the result file, providing a final cap to the file that gives the user as much appropriate data as necessary in a concise, easy-to-read format for further study and verification outside the program.

Mathematical Model

Using two initial angle measurements, β and ζ, and estimations of fluid velocity from the Elmer model, the value of circulation (Γ) was estimated by adjusting the two angles and their corresponding parameters to establish two new congruent angles over the interval between the radii of circulation. This permits direct comparisons of the velocity vectors at each of the radial endpoints at new *x* and *y* velocities.

$$\theta = \frac{\beta + \zeta}{2}$$

$$\xi = \theta - \beta$$

$$\phi = \tan^{-1}\left(\frac{v_{y\beta}}{v_{x\beta}}\right)$$

$$\psi = \tan^{-1}\left(\frac{v_{y\zeta}}{v_{x\zeta}}\right)$$

$$v_{(abs\beta)} = \sqrt{v_{x\beta}^2 + v_{y\beta}^2}$$

$$v_{(abs\zeta)} = \sqrt{v_{x\zeta}^2 + v_{y\zeta}^2}$$

$$x_c = v_{(abs\beta)} * \cos(\phi + \xi)$$

$$x_d = v_{(abs\zeta)} * \cos(\psi + \xi)$$

Since the circulation creates in this modified state the only source of variation in the flow and since the magnitude of its effect is constant in the *y* axis, there is only one source of variation along the *x* axis where the circulation impels the flow in opposite directions above and below the airfoil.

$$v(y\Gamma) = \frac{x_c - x_d}{2 * \tan\theta}$$

$$v = \frac{v(y\Gamma)}{\cos\theta}$$

$$r = \frac{chord}{2}$$

$$\Gamma = 2\pi * v * r$$

Subtracting the appropriate parameter of *v* to equalize flow on each side gives a solution to *v* that may be correspondingly implemented for lift and against the standard lift formula for the airfoils.

$$L = \frac{1}{2} * C_L * \rho * V^2 * A$$

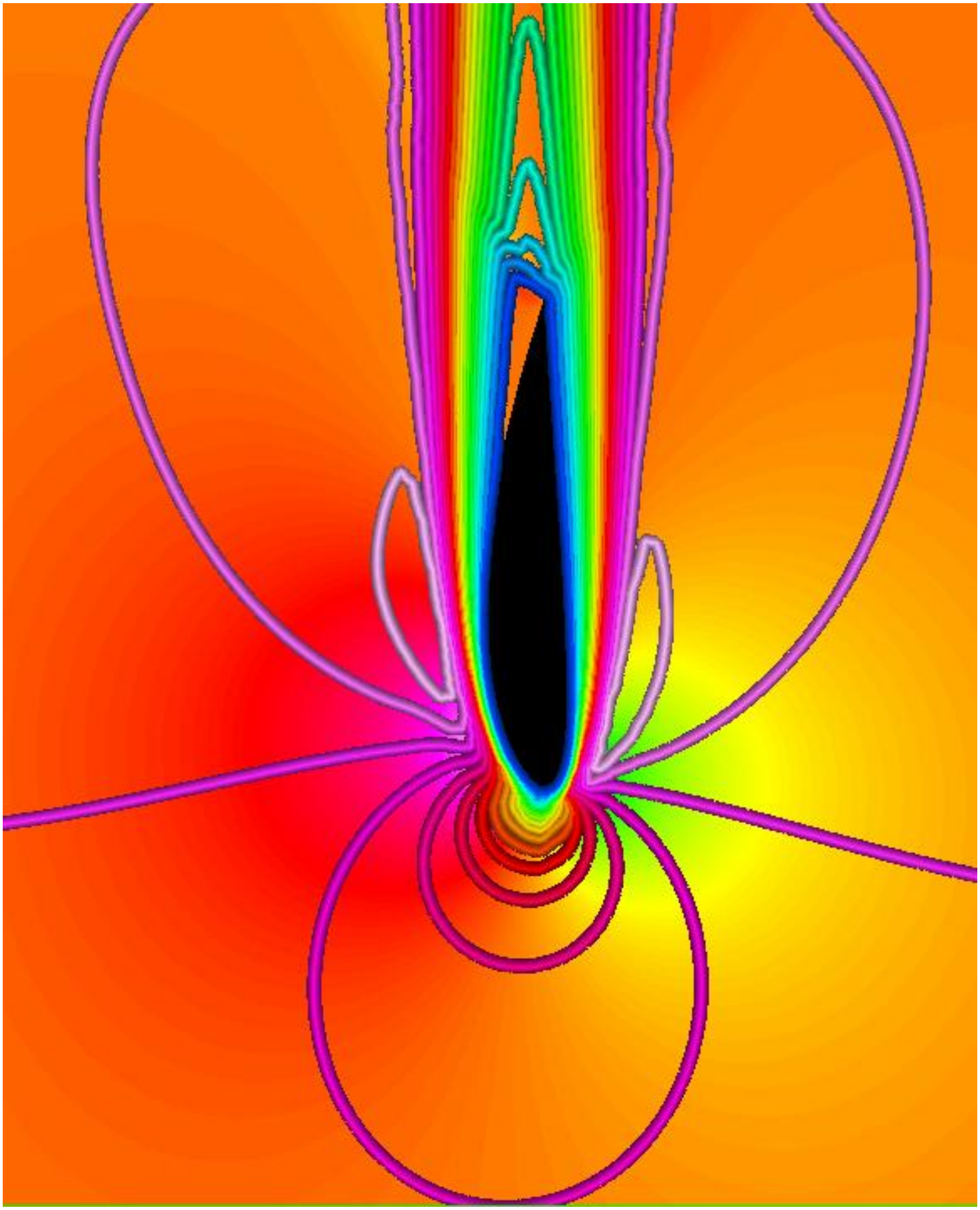
$$L = \rho * V * \Gamma$$

Results and Continuing Work

To date, the project has yielded a successful demonstration of KUJO's ability to write individual files, as well as read those files that it produces, unfortunately, this has not continued into the files produced within ELMER. Difficulties in automatically isolating data points within ELMER by KUJO have resulted in breakdowns that have severely hampered the smooth iterations targeted by the program. This has forced the user to input data manually, which in turn obliges them to remain an active participant in the program instead of the passive ideal that allows the computer to independently solve the problem.

Thus, where the two independent programs meld, there is a fault point in the project that merits continuing efforts. The essential ability of the program to accurately and precisely identify appropriate data points in the FEM solution will be established in future builds of the program to bind the otherwise successful programs into one process. This allows the user to successfully optimize airfoil design with little personal effort where significant research and testing would otherwise be required.

Furthermore, future work stands to allow optimization of other devices as well, allowing the user to define their own fundamental geometry designs and test for any feature allowed for within ELMER. At the moment, KUJO uses a basic airfoil design as reference to initiate the process, allowing the user to define features of scale, material, and environmental surroundings. This can be improved within KUJO to allow the multi-physics capabilities of ELMER to reach full potential, particularly as the latter expands its capabilities to new levels with successive releases. This work would certainly be expanded over significant periods of time, however, and holds little immediate priority.



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Appendices

Sample Files:

*.EGF file

```
Header
        Name "xfoil4418x"
        Dimension 2
End

Vertices
        points
                Variable Index
                Size 2
                Real

1       1.000000   0.001890
2       0.991380   0.004836
3       0.977106   0.009636
4       0.961189   0.014875
5       0.943716   0.020491
6       0.924880   0.026390
7       0.904944   0.032460
8       0.884178   0.038596
9       0.862817   0.044713
10      0.841045   0.050745
11      0.818994   0.056649
12      0.796754   0.062395
13      0.774389   0.067962
14      0.751940   0.073339
15      0.729438   0.078514
16      0.706907   0.083480
17      0.684364   0.088230
18      0.661825   0.092757
19      0.639304   0.097056
20      0.616815   0.101120
21      0.594371   0.104942
22      0.571989   0.108515
23      0.549684   0.111832
24      0.527474   0.114883
25      0.505384   0.117662
26      0.483441   0.120159
27      0.461681   0.122364
28      0.440152   0.124270
29      0.418919   0.125868
30      0.398070   0.127152
31      0.377672   0.128051
32      0.357643   0.128530
33      0.337934   0.128596
34      0.318529   0.128251
35      0.299431   0.127497
```

36	0.280656	0.126337
37	0.262234	0.124774
38	0.244205	0.122817
39	0.226616	0.120476
40	0.209526	0.117768
41	0.193002	0.114718
42	0.177112	0.111356
43	0.161931	0.107721
44	0.147528	0.103860
45	0.133960	0.099822
46	0.121271	0.095662
47	0.109484	0.091430
48	0.098598	0.087173
49	0.088594	0.082933
50	0.079433	0.078740
51	0.071066	0.074617
52	0.063437	0.070579
53	0.056484	0.066636
54	0.050149	0.062789
55	0.044376	0.059039
56	0.039113	0.055382
57	0.034313	0.051812
58	0.029935	0.048323
59	0.025942	0.044908
60	0.022305	0.041560
61	0.018996	0.038271
62	0.015994	0.035034
63	0.013280	0.031843
64	0.010840	0.028693
65	0.008663	0.025578
66	0.006740	0.022495
67	0.005065	0.019442
68	0.003635	0.016418
69	0.002446	0.013424
70	0.001497	0.010466
71	0.000784	0.007547
72	0.000302	0.004673
73	0.000049	0.001864
74	0.000011	-0.000880
75	0.000192	-0.003641
76	0.000617	-0.006445
77	0.001309	-0.009256
78	0.002283	-0.012053
79	0.003553	-0.014813
80	0.005121	-0.017515
81	0.006985	-0.020140
82	0.009140	-0.022677
83	0.011580	-0.025117
84	0.014300	-0.027459
85	0.017297	-0.029703
86	0.020573	-0.031853
87	0.024135	-0.033913
88	0.027995	-0.035888
89	0.032169	-0.037784
90	0.036680	-0.039604
91	0.041559	-0.041352

92	0.046840	-0.043032
93	0.052570	-0.044644
94	0.058800	-0.046188
95	0.065595	-0.047664
96	0.073029	-0.049066
97	0.081190	-0.050389
98	0.090177	-0.051622
99	0.100101	-0.052752
100	0.111081	-0.053762
101	0.123239	-0.054631
102	0.136688	-0.055333
103	0.151518	-0.055843
104	0.167777	-0.056135
105	0.185466	-0.056190
106	0.204526	-0.055996
107	0.224851	-0.055555
108	0.246300	-0.054879
109	0.268719	-0.053991
110	0.291955	-0.052923
111	0.315857	-0.051711
112	0.340279	-0.050393
113	0.365061	-0.049011
114	0.390007	-0.047605
115	0.414891	-0.046188
116	0.439707	-0.044657
117	0.464568	-0.043014
118	0.489530	-0.041274
119	0.514617	-0.039452
120	0.539836	-0.037562
121	0.565184	-0.035617
122	0.590648	-0.033630
123	0.616212	-0.031614
124	0.641853	-0.029580
125	0.667540	-0.027537
126	0.693233	-0.025495
127	0.718904	-0.023463
128	0.744532	-0.021445
129	0.770097	-0.019445
130	0.795563	-0.017468
131	0.820870	-0.015517
132	0.845910	-0.013600
133	0.870511	-0.011728
134	0.894406	-0.009917
135	0.917235	-0.008190
136	0.938585	-0.006575
137	0.958087	-0.005096
138	0.975523	-0.003768
139	0.990866	-0.002593
140	1.000000	-0.001890
141	3	-1.5
142	-3	-1.5
143	-3	1.5
144	3	1.5

End
End

Edge 1
Name "Top"
Vertices 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73
End

Edge 2
Name "Bottom"
Vertices 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119 120 121 122 123 124 125 126 127 128 129 130 131 132 133 134 135 136 137 138 139 140
End

Edge 3
Name "Front"
Vertices 141 142 143 144
End

Edge 4
Name "Back_up"
Vertices 144 1
End

Edge 5
Name "Back_down"
Vertices 141 140
End

Edge 6
Name "Back"
Vertices 144 141
End

Edge 7
Name "airfoil back"
Vertices 1 140
End

Body 1
Name "airfoil"
Color 255 54 100 139
Edges 1 2 5 3 4
End

Body 2
Name "BackSeg"
Color 255 54 100 139
Edges 4 6 5 7
End

*.EMF file

```
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!Saved       = Wed Mar 15 14:11:46 2006 User=supercomputing Host=PC7
!Case        = xfoil4418x  0AOA
!Model dir   = E:/elmerx/ELMER4.0/bin/xfoil4418x
!Include path =
!Results dir  =
!Log dir      =

Header
  Created "Wed Mar 15 12:55:46 2006 User=oscar Host=PC7"
  Modified "Wed Mar 15 14:11:46 2006 User=supercomputing Host=PC7"
  Has Definitions 1
  Elmer Front Version 9
  Timestamp "Wed Mar 15 14:11:46 2006"
  Model Status 0
  Model Source Type 0
  Cad Source File "E:/elmerx/xfoil4418x.egf"
  Mesh Result File ""
  Model Name "xfoil4418x"
  Problem Name "0AOA"
  Model Description ""
  Problem Description ""
  Matc File Emf ""
  Matc File Sif ""
  Nof Processors 1
  Dimension 2
  Minimum Edge Size 0.00274426
  Mesh Names
    Size 1
      String "mesh1"
  Current Mesh Index 0
  Mesh H 0.0274426
  Mesh F 1
End

Timestamps
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  Database "Wed Mar 15 14:11:43 2006"
  Grid Parameter ""
  Mesh ""
  Solver "Wed Mar 15 14:11:46 2006"
  GebhardtFactors ""
  ViewFactors ""
End

Statistics
  Nof Bodies 2
  Nof Loops 2
  Nof Elements 7
  Nof Outer Boundaries 5
  Nof Inner Boundaries 2
  Nof Vertices 144
  Max Loop Count 5
```

End

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OUTPUT_CALLER==True|EXEC_SOLVER==Always"
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  Name "Constant1"
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08|PERMITTIVITY_OF_VACUUM==8.8542e-12"
End

Coordinate 1
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End

Datafile 1
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  Data
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418x.0AOA.dat|POST_FILE==xfoil4418x.0AOA.ep|GEBHARDT_FACTORS==GebhardtFactors.dat|VIEW_FAC
TORS==Viewfactors.dat"
End

Equation Variable 1
  Name "EquationVariable1"
  Data
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STICITY==Displacement|MESH_UPDATE==Mesh Update|AXISYMM._MAG._VEC._POT.==Magnetic Vector
Potential|MAGNETIC_INDUCTION==Magnetic
Field|ELECTROSTATICS==Potential|STATIC_CURRENT_CONDUCTION==Potential|PLATE_ELASTICITY=
=Deflection|REDUCED_ELECTROSTATICS==ElectricForce|HARMONIC_REYNOLDS_EQUATION==Pressur
e|TRANSIENT_REYNOLDS_EQUATION==Pressure"
End

Equation 1
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STOKES==True|HYDROSTATIC_PRESSURE==False|KE_TURBULENCE==False|KE_CLIP==1.0e-
06|HEAT_EQUATION==False|CONVECTION==None;|STRESS_ANALYSIS==False|PLANE_STRESS==False|
HELMHOLTZ_EQUATION==False|NONLINEAR_ELASTICITY==False|MESH_UPDATE==True|MESH_UPD
ATE_vars==Mesh
Update|AXISYMM._MAG._VEC._POT.==False|MAGNETIC_INDUCTION==False|ELECTROSTATICS==False
|CALCULATE_ELECTRIC_FIELD_ES==True|CALCULATE_ELECTRIC_FLUX_ES==True|CALCULATE_EL
ECTRIC_ENERGY==False|CONSTANT_WEIGHTS_ES==False|CALCULATE_CAPACITANCE_MATRIX==F
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Solver 2
 Name "Solver2"
 Data "ACTIVE==True|EXEC_SOLVER==Always|EQUATION==Mesh Update|SOLVING_ORDER==2|MESH==mesh1|VARIABLE==Mesh Update|VARIABLE_DOFS==2|PROCEDURE==MeshSolve;MeshSolver|LINEAR_SYSTEM_SOLVER==Iterative|-LINEAR_SYSTEM_DIRECT_METHOD==BANDED|LINEAR_SYSTEM_ITERATIVE_METHOD==BiCGStab|-LINEAR_SYSTEM_MULTIGRID_METHOD==Jacobi|LINEAR_SYSTEM_MAX_ITERATIONS==300|LINEAR_SYSTEM_CONVERGENCE_TOLERANCE==1.0e-08|LINEAR_SYSTEM_ABORT_NOT_CONVERGED==True|LINEAR_SYSTEM_PRECONDITIONING==ILU0|-LINEAR_SYSTEM_ILUT_TOLERANCE==1.0e-03|LINEAR_SYSTEM_RESIDUAL_OUTPUT==1|STEADY_STATE_CONVERGENCE_TOLERANCE==1.0e-05|-MG_LEVELS==1|-MG_EQUAL_SPLIT==True|-MG_SMOOTHER==Jacobi|-

MG_PRE_SMOOTHING_ITERATIONS==5|-MG_POST_SMOOTHING_ITERATIONS==5|-
MG_MAX_ITERATIONS==300|-MG_CONVERGENCE_TOLERANCE==1.0e-08|-
MG_PRECONDITIONING==ILU0|-MG_ILUT_TOLERANCE==1.0e-03|-STABILIZE==True|-
BUBBLES==False|-LUMPED_MASS_MATRIX==False|-
NONLINEAR_SYSTEM_CONVERGENCE_TOLERANCE==1.0e-05|-
NONLINEAR_SYSTEM_MAX_ITERATIONS==1|-
NONLINEAR_SYSTEM_NEWTON_AFTER_ITERATIONS==3|-
NONLINEAR_SYSTEM_NEWTON_AFTER_TOLERANCE==1.0e-
02|NONLINEAR_SYSTEM_RELAXATION_FACTOR==1|LINEAR_SYSTEM_PRECONDITION_RECOMPUT
E==1|-ADAPTIVE_ERROR_LIMIT==0.1|-ADAPTIVE_REMESH==True|-ADAPTIVE_MAX_CHANGE==2|-
ADAPTIVE_COARSENING==True|-EIGEN_ANALYSIS==False|-TIME_DERIVATIVE_ORDER==2|-
EIGEN_SYSTEM_DAMPED==False|-EIGEN_SYSTEM_USE_IDENTITY==True"
End

Timestep 1
  Name "Timestep1"
  Data
"ACTIVE==True|TIMESTEPPING_METHOD==Newmark|NEWMARK_BETA==1|BDF_ORDER==1|SIMULAT
ION_TYPE==Steady
State|STEADY_STATE_MAX_ITERATIONS==20|STEADY_STATE_OUTPUT_INTERVAL==1"
End

Vertex Table
  Points
    Size 144 2
      Real
      1 0.00189
      0.99138 0.004836
      0.977106 0.009636
      0.961189 0.014875
      0.943716 0.020491
      0.92488 0.02639
      0.904944 0.03246
      0.884178 0.038596
      0.862817 0.044713
      0.841045 0.050745
      0.818994 0.056649
      0.796754 0.062395
      0.774389 0.067962
      0.75194 0.073339
      0.729438 0.078514
      0.706907 0.08348
      0.684364 0.08823
      0.661825 0.092757
      0.639304 0.097056
      0.616815 0.10112
      0.594371 0.104942
      0.571989 0.108515
      0.549684 0.111832
      0.527474 0.114883
      0.505384 0.117662
      0.483441 0.120159
      0.461681 0.122364
      0.440152 0.12427
      0.418919 0.125868
      0.39807 0.127152

0.377672 0.128051
0.357643 0.12853
0.337934 0.128596
0.318529 0.128251
0.299431 0.127497
0.280656 0.126337
0.262234 0.124774
0.244205 0.122817
0.226616 0.120476
0.209526 0.117768
0.193002 0.114718
0.177112 0.111356
0.161931 0.107721
0.147528 0.10386
0.13396 0.099822
0.121271 0.095662
0.109484 0.09143
0.098598 0.087173
0.088594 0.082933
0.079433 0.07874
0.071066 0.074617
0.063437 0.070579
0.056484 0.066636
0.050149 0.062789
0.044376 0.059039
0.039113 0.055382
0.034313 0.051812
0.029935 0.048323
0.025942 0.044908
0.022305 0.04156
0.018996 0.038271
0.015994 0.035034
0.01328 0.031843
0.01084 0.028693
0.008663 0.025578
0.00674 0.022495
0.005065 0.019442
0.003635 0.016418
0.002446 0.013424
0.001497 0.010466
0.000784 0.007547
0.000302 0.004673
4.9e-005 0.001864
1.1e-005 -0.00088
0.000192 -0.003641
0.000617 -0.006445
0.001309 -0.009256
0.002283 -0.012053
0.003553 -0.014813
0.005121 -0.017515
0.006985 -0.02014
0.00914 -0.022677
0.01158 -0.025117
0.0143 -0.027459
0.017297 -0.029703
0.020573 -0.031853

0.024135 -0.033913
0.027995 -0.035888
0.032169 -0.037784
0.03668 -0.039604
0.041559 -0.041352
0.04684 -0.043032
0.05257 -0.044644
0.0588 -0.046188
0.065595 -0.047664
0.073029 -0.049066
0.08119 -0.050389
0.090177 -0.051622
0.100101 -0.052752
0.111081 -0.053762
0.123239 -0.054631
0.136688 -0.055333
0.151518 -0.055843
0.167777 -0.056135
0.185466 -0.05619
0.204526 -0.055996
0.224851 -0.055555
0.2463 -0.054879
0.268719 -0.053991
0.291955 -0.052923
0.315857 -0.051711
0.340279 -0.050393
0.365061 -0.049011
0.390007 -0.047605
0.414891 -0.046188
0.439707 -0.044657
0.464568 -0.043014
0.48953 -0.041274
0.514617 -0.039452
0.539836 -0.037562
0.565184 -0.035617
0.590648 -0.03363
0.616212 -0.031614
0.641853 -0.02958
0.66754 -0.027537
0.693233 -0.025495
0.718904 -0.023463
0.744532 -0.021445
0.770097 -0.019445
0.795563 -0.017468
0.82087 -0.015517
0.84591 -0.0136
0.870511 -0.011728
0.894406 -0.009917
0.917235 -0.00819
0.938585 -0.006575
0.958087 -0.005096
0.975523 -0.003768
0.990866 -0.002593
1 -0.00189
3 -1.5
-3 -1.5

```
    -3 1.5
    3 1.5
End

Vertex 1
  Boundary Tag 8
  Name "Vertex1"
End

Vertex 2
  Boundary Tag 9
  Name "Vertex2"
End

Vertex 3
  Boundary Tag 10
  Name "Vertex3"
End

Vertex 4
  Boundary Tag 11
  Name "Vertex4"
End

Vertex 5
  Boundary Tag 12
  Name "Vertex5"
End

Vertex 6
  Boundary Tag 13
  Name "Vertex6"
End

Vertex 7
  Boundary Tag 14
  Name "Vertex7"
End

Vertex 8
  Boundary Tag 15
  Name "Vertex8"
End

Vertex 9
  Boundary Tag 16
  Name "Vertex9"
End

Vertex 10
  Boundary Tag 17
  Name "Vertex10"
End

Vertex 11
  Boundary Tag 18
```

```
  Name "Vertex11"
End

Vertex 12
  Boundary Tag 19
  Name "Vertex12"
End

Vertex 13
  Boundary Tag 20
  Name "Vertex13"
End

Vertex 14
  Boundary Tag 21
  Name "Vertex14"
End

Vertex 15
  Boundary Tag 22
  Name "Vertex15"
End

Vertex 16
  Boundary Tag 23
  Name "Vertex16"
End

Vertex 17
  Boundary Tag 24
  Name "Vertex17"
End

Vertex 18
  Boundary Tag 25
  Name "Vertex18"
End

Vertex 19
  Boundary Tag 26
  Name "Vertex19"
End

Vertex 20
  Boundary Tag 27
  Name "Vertex20"
End

Vertex 21
  Boundary Tag 28
  Name "Vertex21"
End

Vertex 22
  Boundary Tag 29
  Name "Vertex22"
```

```
End

Vertex 23
 Boundary Tag 30
 Name "Vertex23"
End

Vertex 24
 Boundary Tag 31
 Name "Vertex24"
End

Vertex 25
 Boundary Tag 32
 Name "Vertex25"
End

Vertex 26
 Boundary Tag 33
 Name "Vertex26"
End

Vertex 27
 Boundary Tag 34
 Name "Vertex27"
End

Vertex 28
 Boundary Tag 35
 Name "Vertex28"
End

Vertex 29
 Boundary Tag 36
 Name "Vertex29"
End

Vertex 30
 Boundary Tag 37
 Name "Vertex30"
End

Vertex 31
 Boundary Tag 38
 Name "Vertex31"
End

Vertex 32
 Boundary Tag 39
 Name "Vertex32"
End

Vertex 33
 Boundary Tag 40
 Name "Vertex33"
End
```

```
Vertex 34
 Boundary Tag 41
 Name "Vertex34"
End

Vertex 35
 Boundary Tag 42
 Name "Vertex35"
End

Vertex 36
 Boundary Tag 43
 Name "Vertex36"
End

Vertex 37
 Boundary Tag 44
 Name "Vertex37"
End

Vertex 38
 Boundary Tag 45
 Name "Vertex38"
End

Vertex 39
 Boundary Tag 46
 Name "Vertex39"
End

Vertex 40
 Boundary Tag 47
 Name "Vertex40"
End

Vertex 41
 Boundary Tag 48
 Name "Vertex41"
End

Vertex 42
 Boundary Tag 49
 Name "Vertex42"
End

Vertex 43
 Boundary Tag 50
 Name "Vertex43"
End

Vertex 44
 Boundary Tag 51
 Name "Vertex44"
End
```

```
Vertex 45
 Boundary Tag 52
 Name "Vertex45"
End

Vertex 46
 Boundary Tag 53
 Name "Vertex46"
End

Vertex 47
 Boundary Tag 54
 Name "Vertex47"
End

Vertex 48
 Boundary Tag 55
 Name "Vertex48"
End

Vertex 49
 Boundary Tag 56
 Name "Vertex49"
End

Vertex 50
 Boundary Tag 57
 Name "Vertex50"
End

Vertex 51
 Boundary Tag 58
 Name "Vertex51"
End

Vertex 52
 Boundary Tag 59
 Name "Vertex52"
End

Vertex 53
 Boundary Tag 60
 Name "Vertex53"
End

Vertex 54
 Boundary Tag 61
 Name "Vertex54"
End

Vertex 55
 Boundary Tag 62
 Name "Vertex55"
End

Vertex 56
```

```
  Boundary Tag 63
  Name "Vertex56"
End

Vertex 57
  Boundary Tag 64
  Name "Vertex57"
End

Vertex 58
  Boundary Tag 65
  Name "Vertex58"
End

Vertex 59
  Boundary Tag 66
  Name "Vertex59"
End

Vertex 60
  Boundary Tag 67
  Name "Vertex60"
End

Vertex 61
  Boundary Tag 68
  Name "Vertex61"
End

Vertex 62
  Boundary Tag 69
  Name "Vertex62"
End

Vertex 63
  Boundary Tag 70
  Name "Vertex63"
End

Vertex 64
  Boundary Tag 71
  Name "Vertex64"
End

Vertex 65
  Boundary Tag 72
  Name "Vertex65"
End

Vertex 66
  Boundary Tag 73
  Name "Vertex66"
End

Vertex 67
  Boundary Tag 74
```

```
  Name "Vertex67"
End

Vertex 68
  Boundary Tag 75
  Name "Vertex68"
End

Vertex 69
  Boundary Tag 76
  Name "Vertex69"
End

Vertex 70
  Boundary Tag 77
  Name "Vertex70"
End

Vertex 71
  Boundary Tag 78
  Name "Vertex71"
End

Vertex 72
  Boundary Tag 79
  Name "Vertex72"
End

Vertex 73
  Boundary Tag 80
  Name "Vertex73"
End

Vertex 74
  Boundary Tag 81
  Name "Vertex74"
End

Vertex 75
  Boundary Tag 82
  Name "Vertex75"
End

Vertex 76
  Boundary Tag 83
  Name "Vertex76"
End

Vertex 77
  Boundary Tag 84
  Name "Vertex77"
End

Vertex 78
  Boundary Tag 85
  Name "Vertex78"
```

```
End

Vertex 79
 Boundary Tag 86
 Name "Vertex79"
End

Vertex 80
 Boundary Tag 87
 Name "Vertex80"
End

Vertex 81
 Boundary Tag 88
 Name "Vertex81"
End

Vertex 82
 Boundary Tag 89
 Name "Vertex82"
End

Vertex 83
 Boundary Tag 90
 Name "Vertex83"
End

Vertex 84
 Boundary Tag 91
 Name "Vertex84"
End

Vertex 85
 Boundary Tag 92
 Name "Vertex85"
End

Vertex 86
 Boundary Tag 93
 Name "Vertex86"
End

Vertex 87
 Boundary Tag 94
 Name "Vertex87"
End

Vertex 88
 Boundary Tag 95
 Name "Vertex88"
End

Vertex 89
 Boundary Tag 96
 Name "Vertex89"
End
```

```
Vertex 90
 Boundary Tag 97
 Name "Vertex90"
End

Vertex 91
 Boundary Tag 98
 Name "Vertex91"
End

Vertex 92
 Boundary Tag 99
 Name "Vertex92"
End

Vertex 93
 Boundary Tag 100
 Name "Vertex93"
End

Vertex 94
 Boundary Tag 101
 Name "Vertex94"
End

Vertex 95
 Boundary Tag 102
 Name "Vertex95"
End

Vertex 96
 Boundary Tag 103
 Name "Vertex96"
End

Vertex 97
 Boundary Tag 104
 Name "Vertex97"
End

Vertex 98
 Boundary Tag 105
 Name "Vertex98"
End

Vertex 99
 Boundary Tag 106
 Name "Vertex99"
End

Vertex 100
 Boundary Tag 107
 Name "Vertex100"
End
```

```
Vertex 101
  Boundary Tag 108
  Name "Vertex101"
End

Vertex 102
  Boundary Tag 109
  Name "Vertex102"
End

Vertex 103
  Boundary Tag 110
  Name "Vertex103"
End

Vertex 104
  Boundary Tag 111
  Name "Vertex104"
End

Vertex 105
  Boundary Tag 112
  Name "Vertex105"
End

Vertex 106
  Boundary Tag 113
  Name "Vertex106"
End

Vertex 107
  Boundary Tag 114
  Name "Vertex107"
End

Vertex 108
  Boundary Tag 115
  Name "Vertex108"
End

Vertex 109
  Boundary Tag 116
  Name "Vertex109"
End

Vertex 110
  Boundary Tag 117
  Name "Vertex110"
End

Vertex 111
  Boundary Tag 118
  Name "Vertex111"
End

Vertex 112
```

```
  Boundary Tag 119
  Name "Vertex112"
End

Vertex 113
  Boundary Tag 120
  Name "Vertex113"
End

Vertex 114
  Boundary Tag 121
  Name "Vertex114"
End

Vertex 115
  Boundary Tag 122
  Name "Vertex115"
End

Vertex 116
  Boundary Tag 123
  Name "Vertex116"
End

Vertex 117
  Boundary Tag 124
  Name "Vertex117"
End

Vertex 118
  Boundary Tag 125
  Name "Vertex118"
End

Vertex 119
  Boundary Tag 126
  Name "Vertex119"
End

Vertex 120
  Boundary Tag 127
  Name "Vertex120"
End

Vertex 121
  Boundary Tag 128
  Name "Vertex121"
End

Vertex 122
  Boundary Tag 129
  Name "Vertex122"
End

Vertex 123
  Boundary Tag 130
```

```
  Name "Vertex123"
End

Vertex 124
  Boundary Tag 131
  Name "Vertex124"
End

Vertex 125
  Boundary Tag 132
  Name "Vertex125"
End

Vertex 126
  Boundary Tag 133
  Name "Vertex126"
End

Vertex 127
  Boundary Tag 134
  Name "Vertex127"
End

Vertex 128
  Boundary Tag 135
  Name "Vertex128"
End

Vertex 129
  Boundary Tag 136
  Name "Vertex129"
End

Vertex 130
  Boundary Tag 137
  Name "Vertex130"
End

Vertex 131
  Boundary Tag 138
  Name "Vertex131"
End

Vertex 132
  Boundary Tag 139
  Name "Vertex132"
End

Vertex 133
  Boundary Tag 140
  Name "Vertex133"
End

Vertex 134
  Boundary Tag 141
  Name "Vertex134"
```

```
End

Vertex 135
  Boundary Tag 142
  Name "Vertex135"
End

Vertex 136
  Boundary Tag 143
  Name "Vertex136"
End

Vertex 137
  Boundary Tag 144
  Name "Vertex137"
End

Vertex 138
  Boundary Tag 145
  Name "Vertex138"
End

Vertex 139
  Boundary Tag 146
  Name "Vertex139"
End

Vertex 140
  Boundary Tag 147
  Name "Vertex140"
End

Vertex 141
  Boundary Tag 148
  Name "Vertex141"
End

Vertex 142
  Boundary Tag 149
  Name "Vertex142"
End

Vertex 143
  Boundary Tag 150
  Name "Vertex143"
End

Vertex 144
  Boundary Tag 151
  Name "Vertex144"
End

Edge 1
  Boundary Tag 1
  Name "Top"
```

```
  Vertices 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37
38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73
  Boundary Condition 1
  Gridh Ids 1
  Gridh Mesh Indices 0
End

Edge 2
  Boundary Tag 2
  Name "Bottom"
  Vertices 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100 101 102 103 104
105 106 107 108 109 110 111 112 113 114 115 116 117 118 119 120 121 122 123 124 125 126 127 128 129 130
131 132 133 134 135 136 137 138 139 140
  Boundary Condition 1
  Gridh Ids 2
  Gridh Mesh Indices 0
End

Edge 3
  Boundary Tag 3
  Name "Front"
  Vertices 141 142 143 144
  Boundary Condition 2
  Gridh Ids 3
  Gridh Mesh Indices 0
End

Edge 4
  Boundary Tag 4
  Name "Back_up"
  Vertices 144 1
  Boundary Condition 3
  Gridh Ids 4
  Gridh Mesh Indices 0
End

Edge 5
  Boundary Tag 5
  Name "Back_down"
  Vertices 141 140
  Boundary Condition 3
  Gridh Ids 5
  Gridh Mesh Indices 0
End

Edge 6
  Boundary Tag 6
  Name "Back"
  Vertices 144 141
  Boundary Condition 3
  Gridh Ids 6
  Gridh Mesh Indices 0
End

Edge 7
  Boundary Tag 7
```

```
  Name "airfoil back"
  Vertices 1 140
  Boundary Condition 4
  Gridh Ids 7
  Gridh Mesh Indices 0
End

Element Loop 1
  Elements -1 -4 -3 5 -2
End

Element Loop 2
  Elements 4 7 -5 -6
End

Body 1
  Name "airfoil"
  Color 255 54 100 139
  Equation 1
  Material 1
  Element Loops 1
  Grid Parameter Ids 1
  Grid Parameter Mesh Indices 0
End

Body 2
  Name "BackSeg"
  Color 255 54 100 139
  Equation 1
  Material 1
  Element Loops 2
  Grid Parameter Ids 2
  Grid Parameter Mesh Indices 0
End

Boundary Condition 1
  Parent 1
  Parent Type "Element Group"
  Name "Constraint1"
  Data "VELOCITY_1==0|VELOCITY_2==0|-SURFACE_ROUGHNESS==9|-FORCE_BC==False|-
ELECTRIC_FLUX_BC==False|-
CURRENT_DENSITY_BC==False|OPEN_SIDE_REL==False|SYMMETRIC_SIDE==False|OPEN_SIDE_HRE=
=False|OPEN_SIDE_TRE==False"
End

Boundary Condition 2
  Parent 3
  Parent Type "Element Group"
  Name "Constraint2"
  Data "VELOCITY_1==10|VELOCITY_2==0|-SURFACE_ROUGHNESS==9|-FORCE_BC==False|-
ELECTRIC_FLUX_BC==False|-
CURRENT_DENSITY_BC==False|OPEN_SIDE_REL==False|SYMMETRIC_SIDE==False|OPEN_SIDE_HRE=
=False|OPEN_SIDE_TRE==False"
End

Boundary Condition 3
```

```
  Parent 4
  Parent Type "Element Group"
  Name "Constraint3"
  Data "PRESSURE==0|-SURFACE_ROUGHNESS==9|-FORCE_BC==False|-ELECTRIC_FLUX_BC==False|-
CURRENT_DENSITY_BC==False|OPEN_SIDE_REL==False|SYMMETRIC_SIDE==False|OPEN_SIDE_HRE=
=False|OPEN_SIDE_TRE==False"
End

Boundary Condition 4
  Parent 7
  Parent Type "Element Group"
  Name "Constraint4"
  Data "VELOCITY_1==0|VELOCITY_2==0|-SURFACE_ROUGHNESS==9|-FORCE_BC==False|-
ELECTRIC_FLUX_BC==False|-
CURRENT_DENSITY_BC==False|OPEN_SIDE_REL==False|SYMMETRIC_SIDE==False|OPEN_SIDE_HRE=
=False|OPEN_SIDE_TRE==False"
End

Material 1
  Parent 1
  Parent Type "Body"
  Name "Material1"
  Data "DENSITY==1.27|VISCOSITY==0.02|-KE_CMU==0.09|-KE_C1==1.44|-KE_C2==1.92|-
KE_SIGMAK==1|-KE_SIGMAE==1.3|-REFERENCE_PRESSURE==0|-SPECIFIC_HEAT_RATIO==1.4|-
CONVECTION_VELOCITY_1==0|-CONVECTION_VELOCITY_2==0|-CONVECTION_VELOCITY_3==0|-
SOUND_SPEED==340|-DAMPING==0|-RELATIVE_PERMITTIVITY==1|HOLE_TYPE==Round|-
PERMITTIVITY==1|-CONNECTED_APERTURE_FIXED_HRE==False|-
COMPRESSIBILITY_MODEL_HRE==Compressible|-COMPRESSIBILITY_MODEL_TRE==Compressible"
End

Grid Parameter 1
  Parent 1
  Sub Parent 1
  Parent Type "Body"
  Name "MeshStructure1"
  Data
"MESH_ELEMENT_TYPE==Triangle;|MESH_ELEMENT_ORDER==Linear|MESH_LAYER_TYPE==MovingF
ront|MESH_BG_MESH==Delaunay|MESH_DENSITY_TYPE==R;|-MESH_H==0.00274426|MESH_R==1"
End

Grid Parameter 2
  Parent 2
  Sub Parent 2
  Parent Type "Body"
  Name "MeshStructure2"
  Data
"MESH_ELEMENT_TYPE==Triangle;|MESH_ELEMENT_ORDER==Linear|MESH_LAYER_TYPE==MovingF
ront|MESH_BG_MESH==Delaunay|MESH_DENSITY_TYPE==R;|-MESH_H==0.00274426|MESH_R==1"
End

Grid H 1
  Parent 1
  Parent Type "Edge"
  Name "MeshDensity1"
  Data "MESH_DENSITY_TYPE==R;|-MESH_H==0.00274426|MESH_R==1"
End
```

```
Grid H 2
  Parent 2
  Parent Type "Edge"
  Name "MeshDensity2"
  Data "MESH_DENSITY_TYPE==R;|-MESH_H==0.00274426|MESH_R==1"
End

Grid H 3
  Parent 3
  Parent Type "Edge"
  Name "MeshDensity3"
  Data "MESH_DENSITY_TYPE==R;|-MESH_H==0.00274426|MESH_R==1"
End

Grid H 4
  Parent 4
  Parent Type "Edge"
  Name "MeshDensity4"
  Data "MESH_DENSITY_TYPE==R;|-MESH_H==0.00274426|MESH_R==1"
End

Grid H 5
  Parent 5
  Parent Type "Edge"
  Name "MeshDensity5"
  Data "MESH_DENSITY_TYPE==R;|-MESH_H==0.00274426|MESH_R==1"
End

Grid H 6
  Parent 6
  Parent Type "Edge"
  Name "MeshDensity6"
  Data "MESH_DENSITY_TYPE==R;|-MESH_H==0.00274426|MESH_R==1"
End

Grid H 7
  Parent 7
  Parent Type "Edge"
  Name "MeshDensity7"
  Data "MESH_DENSITY_TYPE==R;|-MESH_H==0.00274426|MESH_R==1"
End

!End Of File
```

*.SIF file

```
!ElmerSolver input file from ElmerFront
!Saved       = Wed Mar 15 14:11:43 2006 User=supercomputing Host=PC7
!Case        = xfoil4418x  0AOA
!Model dir   = E:/elmerx/ELMER4.0/bin/xfoil4418x
!Include path =
!Results dir  =

!Bodies 2
!Equations 1
!Solvers 2
!Materials 1
!Body Forces 0
!Initial Conditions 0
!Boundary Conditions 4
!Boundaries 7

!echo on

Header
  CHECK KEYWORDS Warn
  Mesh DB "MESHDIR" "mesh1"
  Include Path ""
  Results Directory ""
End

Simulation
  Min Output Level = 0
  Max Output Level = 31
  Output Caller = True
  Mem Eigen Modes = Integer 1

  Coordinate System = "Cartesian 2D"
  Coordinate Mapping(3) = 1 2 3

  Simulation Type = "Steady State"
  Steady State Max Iterations = 20
  Output Intervals = 1

  Solver Input File = "xfoil4418x.0AOA.sif"
  Output File = "xfoil4418x.0AOA.dat"
  Post File = "xfoil4418x.0AOA.ep"
  Mesh Input File
    File "xfoil4418x.mif"

End

Constants
  Gravity(4) = 0 -1 0 9.82
  Stefan Boltzmann = 5.67e-08
  Permittivity Of Vacuum = 8.8542e-12
End

Body 1
```

```
  Name = "airfoil"

  Equation = 1
  Material = 1
End

Body 2
  Name = "BackSeg"

  Equation = 1
  Material = 1
End

Equation 1
  Name = "Equation1"

  Navier-Stokes = True
  Mesh Update = True
End

Solver 1
  Exec Solver = "Always"
  Equation = "Navier-Stokes"
  Variable = "Flow Solution"
  Variable Dofs = 3
  Linear System Solver = "Iterative"
  Linear System Iterative Method = "BiCGStab"
  Linear System Max Iterations = 500
  Linear System Convergence Tolerance = 1.0e-08
  Linear System Abort Not Converged = True
  Linear System Preconditioning = "ILU0"
  Linear System Residual Output = 1
  Steady State Convergence Tolerance = 1.0e-05
  Stabilize = True
  Nonlinear System Convergence Tolerance = 1.0e-05
  Nonlinear System Max Iterations = 5
  Nonlinear System Newton After Iterations = 3
  Nonlinear System Newton After Tolerance = 1.0e-02
  Nonlinear System Relaxation Factor = 1
  Linear System Precondition Recompute = 1
End

Solver 2
  Exec Solver = "Always"
  Equation = "Mesh Update"
  Variable = "Mesh Update"
  Variable Dofs = 2
  Procedure = "MeshSolve" "MeshSolver"
  Linear System Solver = "Iterative"
  Linear System Iterative Method = "BiCGStab"
  Linear System Max Iterations = 300
  Linear System Convergence Tolerance = 1.0e-08
  Linear System Abort Not Converged = True
  Linear System Preconditioning = "ILU0"
  Linear System Residual Output = 1
  Steady State Convergence Tolerance = 1.0e-05
```

```
  Nonlinear System Relaxation Factor = 1
  Linear System Precondition Recompute = 1
End

Material 1
  Name = "Material1"

  Density = 1.27
  Viscosity = 0.02
  Hole Type = "Round"
End

Boundary Condition 1
  Name = "Constraint1"
  Target Boundaries(2) = 1 2

  Velocity 1 = 0
  Velocity 2 = 0
End

Boundary Condition 2
  Name = "Constraint2"
  Target Boundaries(1) = 3

  Velocity 1 = 10
  Velocity 2 = 0
End

Boundary Condition 3
  Name = "Constraint3"
  Target Boundaries(3) = 4 5 6

  Pressure = 0
End

Boundary Condition 4
  Name = "Constraint4"
  Target Boundaries(1) = 7

  Velocity 1 = 0
  Velocity 2 = 0
End

!End Of File
```