

Wing Configuration Study

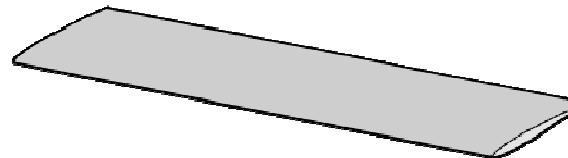
Charles O'Neill

11 Dec 2006

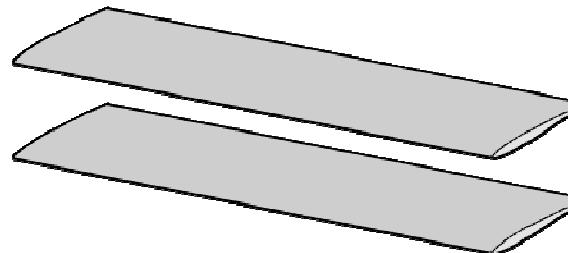
Objective

The primary objective is to study and compare the aerodynamics of various aircraft configurations and geometries for use by the 2007 DBF capstone designers. Particular emphasis is placed on configurations with low aspect ratios. The experiments are performed with a CFD solver. The report contains plots of C_L , C_{D_i} , $C_{L\alpha}$, C_p , and visualizations of flowfields. The final report is in a handbook/gallery format.

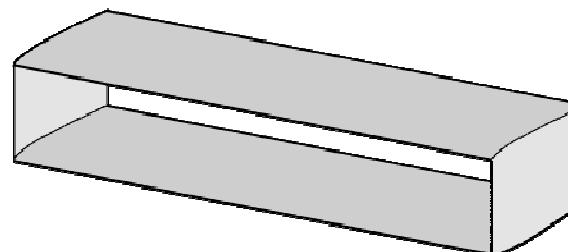
Generic Geometries



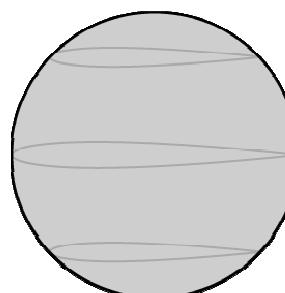
Monoplane



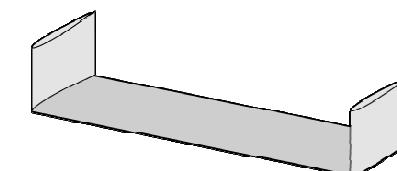
Biplane



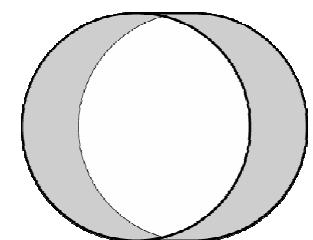
Joined Biplane
"Box"



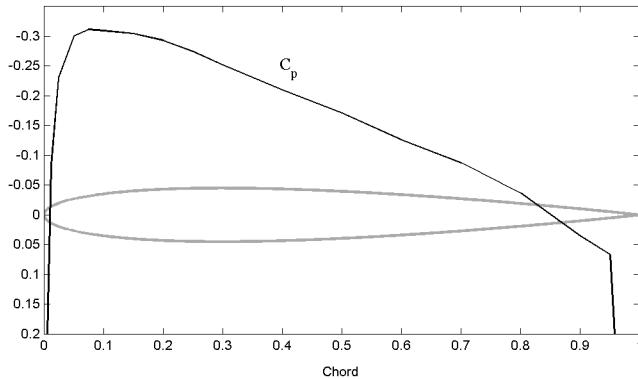
Disc



Monoplane
Endplates



Shroud/Cowl

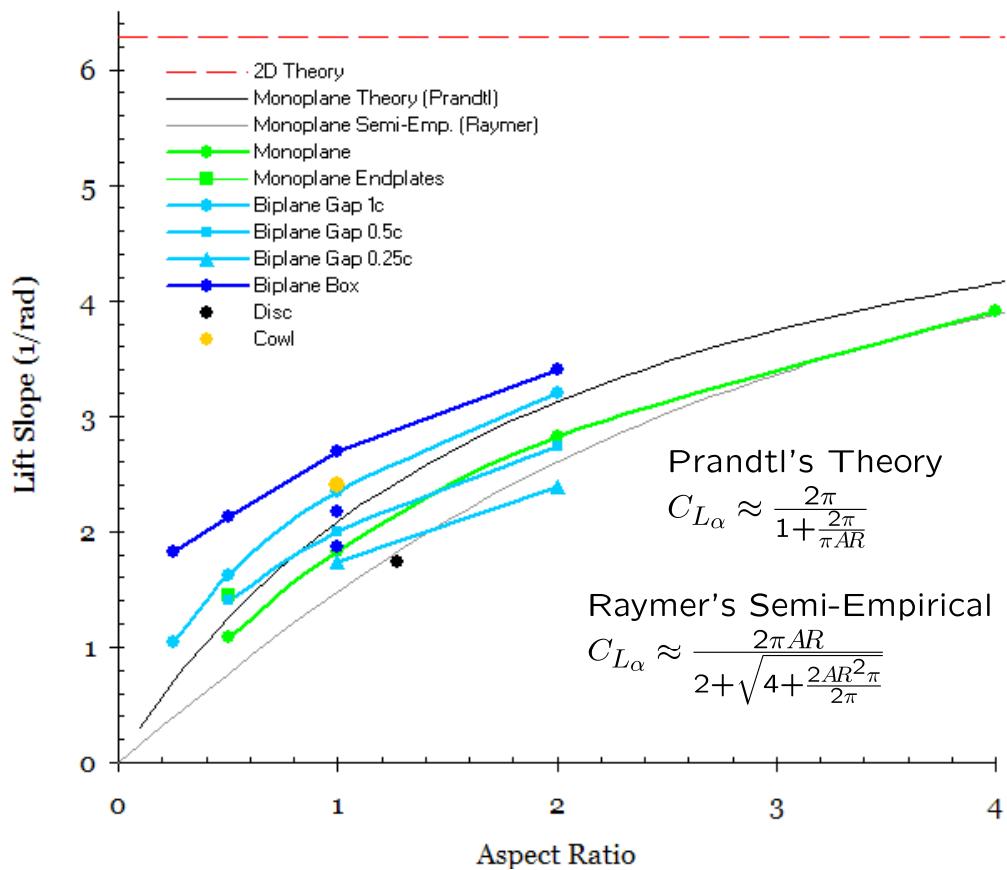


Lift Summary

Lift Slope:

A subsonic wing's $C_{L\alpha}$ primarily depends on its aspect ratio, AR . Two-dimensional theory gives $C_{L\alpha} = 2\pi$. Decreasing AR decreases the lift slope.

A biplane's aspect ratio is half that of the monoplane's aspect ratio for the same chord and tip-to-tip span, but the total wing area is double.



Biplane Gap:

Decreasing a Biplane's gap between the wings decreases $C_{L\alpha}$. $C_{L\alpha}$ decreases 85% from gap 1.0 to 0.5 and 87% from gap 0.5 to 0.25. We will see later that induced drag is also increased. Avoid closely spaced biplane wings.

Endplates:

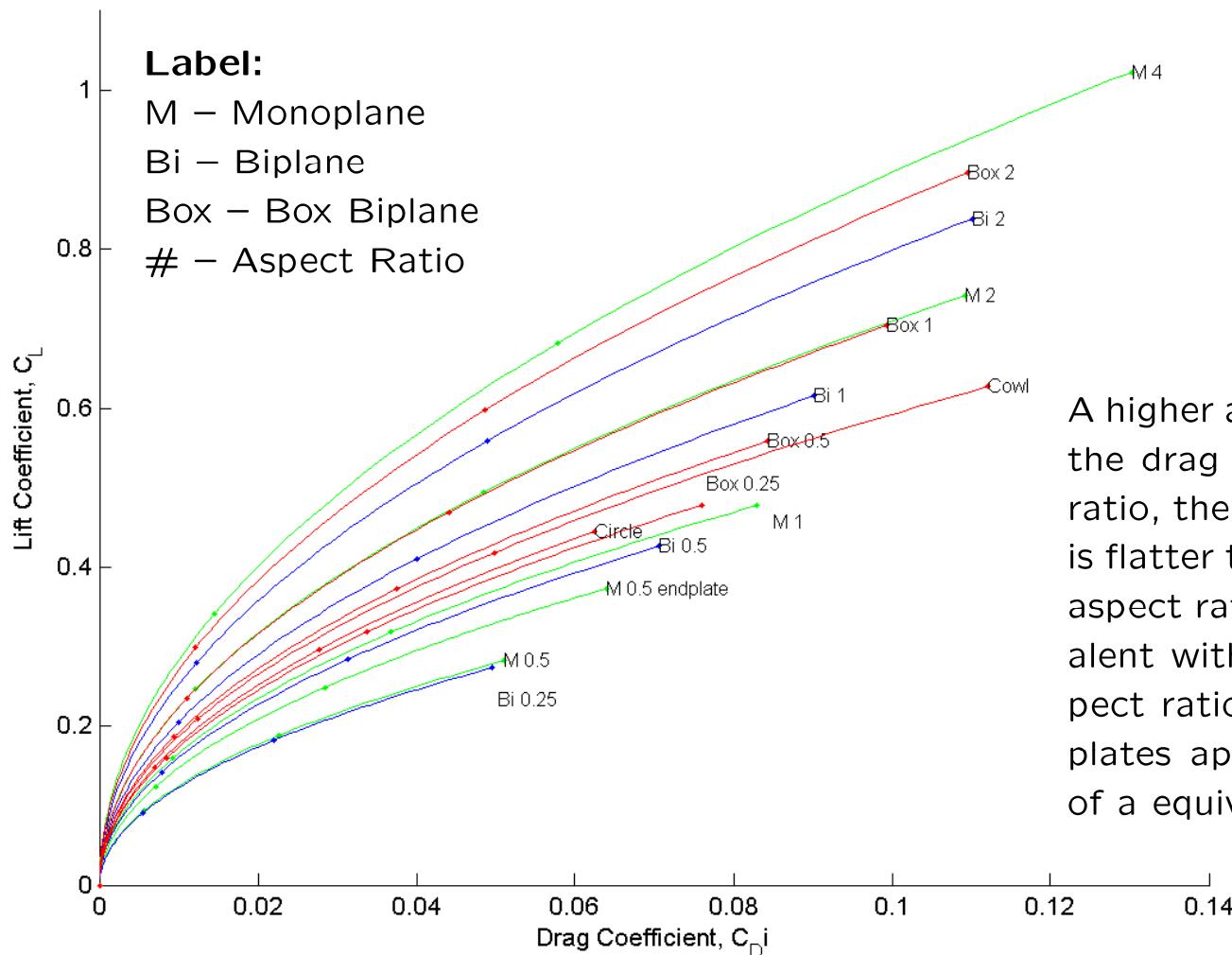
Endplates significantly increase $C_{L\alpha}$. The box biplane is a biplane with "connecting" endplates. The $AR = 0.5$ monoplane increased $C_{L\alpha}$ by 34% by adding $h/b = 0.2$ endplates. Raymer (12.10) predicts an effective $AR = 0.7$ or approximately an increase in $C_{L\alpha}$ of 30%. Notice that the Cowl's $C_{L\alpha}$ is equivalent to a regular biplane; the Cowl's rounded "endplates" do nothing for lift.

A study of endplate thickness revealed a negligible 2% decrease in $C_{L\alpha}$ by decreasing endplate thickness from 9% to 2%. For further details see the box biplane section.

Drag Summary

Drag:

This polar plot, C_L vs. C_{Di} , gives monoplane (M), biplane (bi), box biplane (box), and miscellaneous other geometries. Points are shown at α 5, 10, and 15 degrees.



A higher aspect ratio always improves the drag polar. For a given aspect ratio, the drag polar of a box biplane is flatter than the biplane. For small aspect ratios, a monoplane is equivalent with a biplane of half the aspect ratio. A monoplane with endplates approaches the performance of a equivalent box biplane.

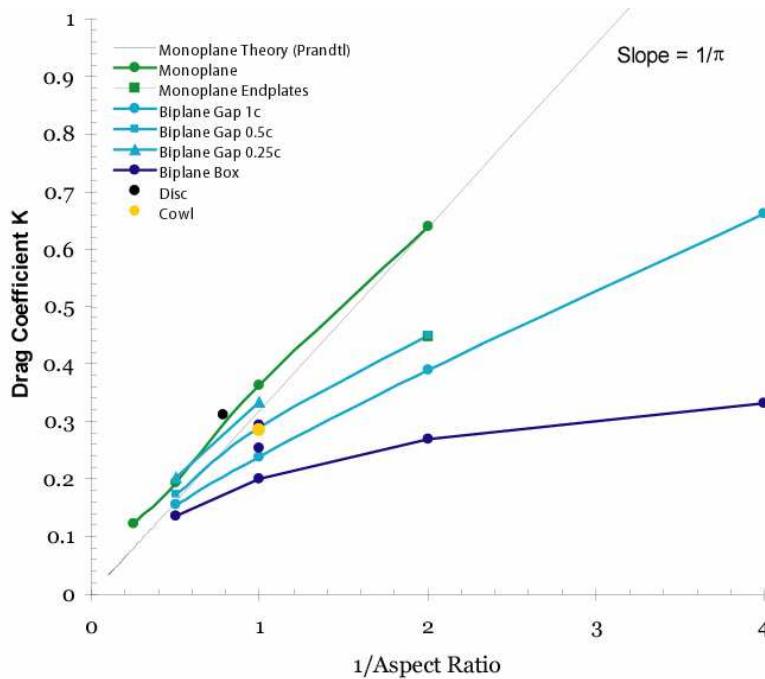
Drag Summary

Drag:

A subsonic wing's induced drag C_{D_i} primarily depends on its aspect ratio. Theory gives

$$C_{D_i} = \frac{1}{\pi AR e} C_L^2 = K C_L^2$$

Measuring the slope of K versus $1/AR$ indicates the non-elliptical efficiency term, e. As aspect ratio decreases the drag efficiency order is: box, biplane, monoplane. Also, increasing biplane gap decreases drag.

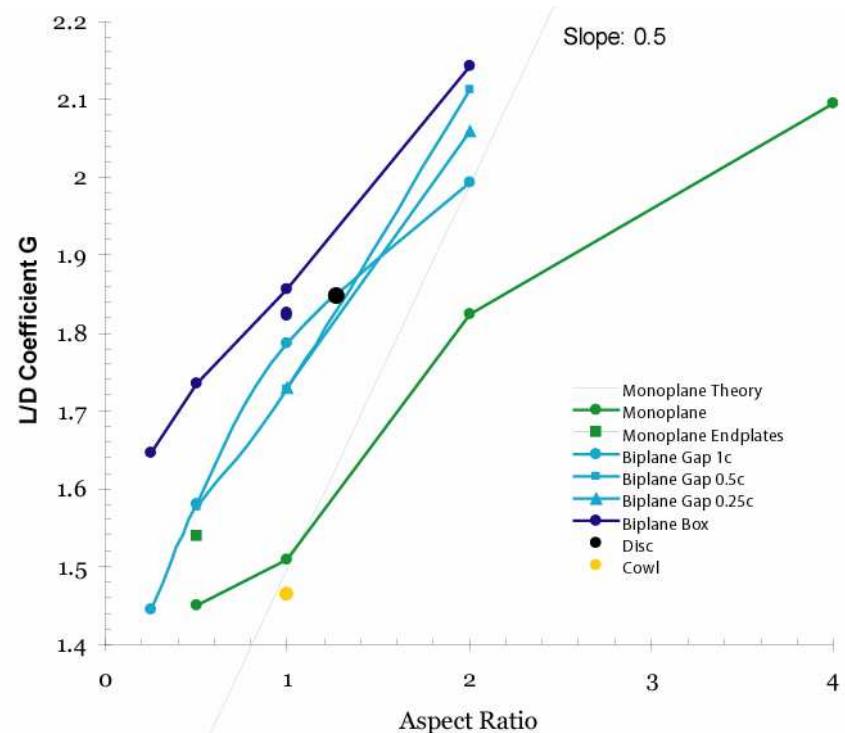


L/D:

The L/D_i ratio is:

$$\frac{L}{D} = \frac{1}{K C_{L_\alpha}} \frac{1}{\alpha} = G \frac{1}{\alpha}$$

Plotting G versus AR gives an indication of efficiency. The efficiency order is: box, biplane, monoplane. The box biplane's L/D advantage over the monoplane is about 20%.

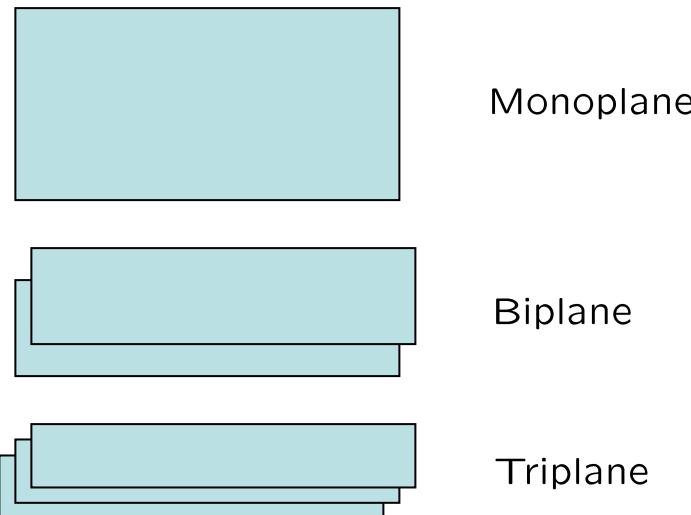


Constrained Span

Constrained Span:

For a constrained span, planform geometry is the only degree of freedom (ie. specifying AR sets chord and area.) Comparing equal AR provides a valid comparison of characteristics when given a constrained span. For an infinite biplane gap (no mutual interaction), a biplane has a $C_{L\alpha}$ ratio advantage over the monoplane of $(\frac{AR+2}{AR+1})$ and half the induced drag. Actual gaps reduce this advantage; see Hoerner.

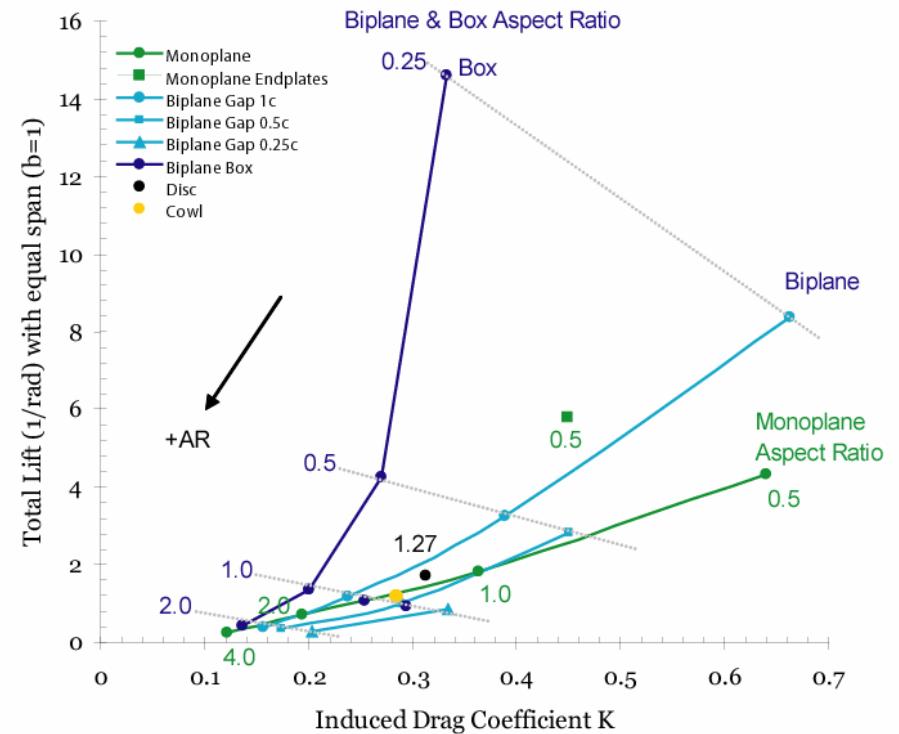
Equal Span and Area:



Total Lift vs. K:

For a constrained span, wing characteristics depend only on the planform geometry. For this experiment, span is set to 1.0; aspect ratio and surface area vary. For aspect ratios below about 2.0, the performance order is: box, biplane, monoplane. Small biplane gaps are detrimental.

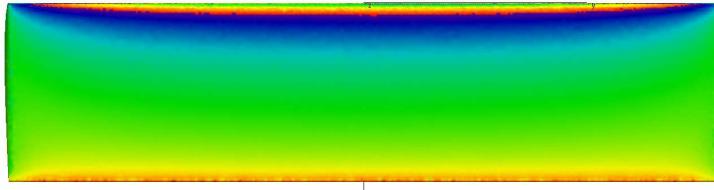
Warning: Wing Area is only constant for equal AR!



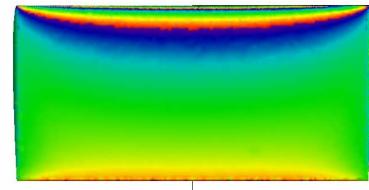
Monoplane

Surface Pressure C_P :

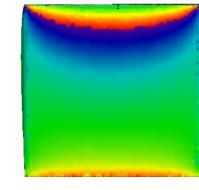
AR 4.0



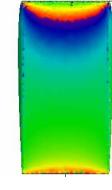
AR 2.0



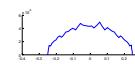
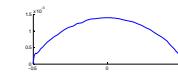
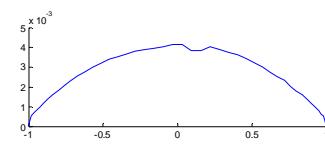
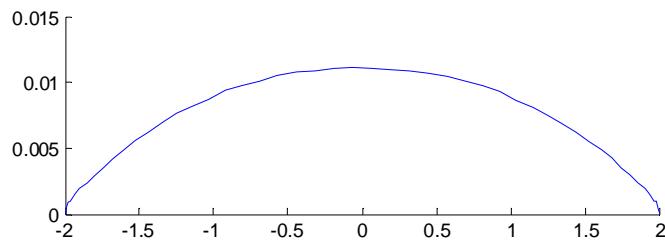
AR 1.0



AR 0.5



Sectional Lift:



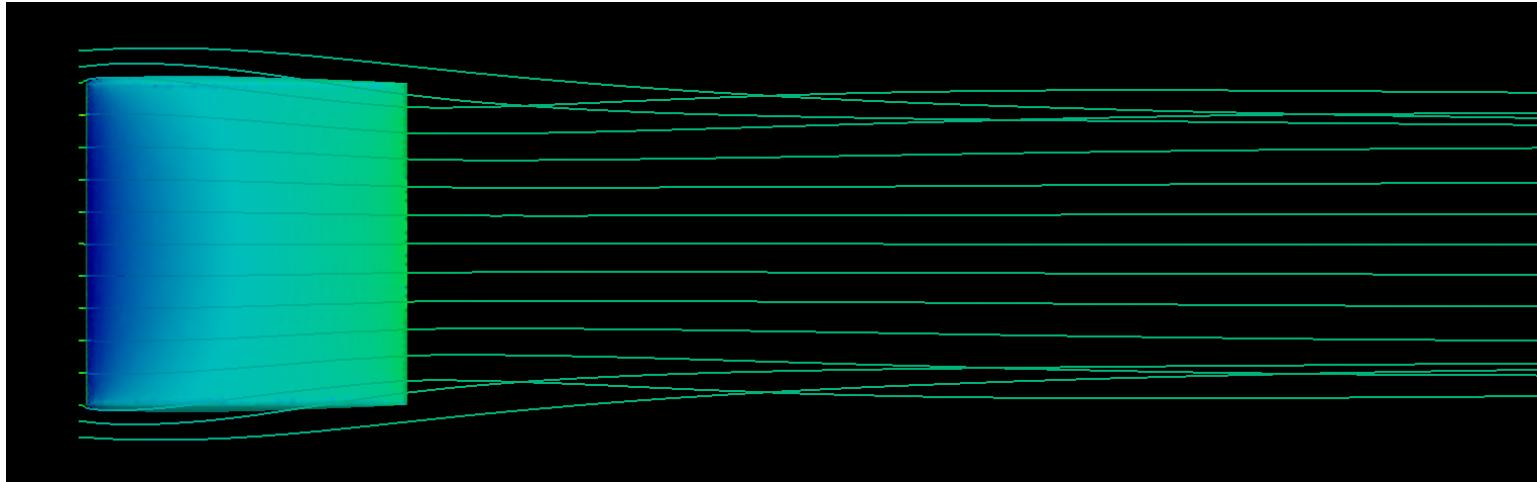
Discussion:

The upper images show the upper surface pressure for the monoplane at an angle of attack of 5 degrees. The leading edge suction is visible. The sectional lift distribution shown in the lower images shows a chordwise-integrated pressure plot along the span.

In spite of the wing's constant chord, the sectional lift distribution strongly approaches an elliptical distribution.

Monoplane: Wake Roll-up

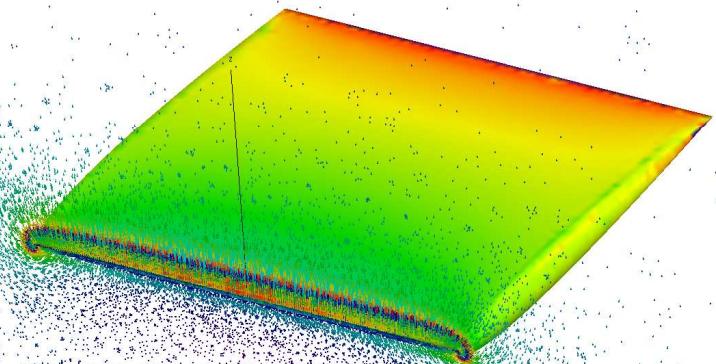
$AR = 1, \alpha = 5^\circ$



Wake Roll-up:

The trailing vortex position determines the aerodynamic aspect ratio. Visually, the effective aspect ratio appears to be about 80% of the geometric aspect ratio ($AR = 0.8$ gives 25% greater induced drag and 15% lower $C_{L\alpha}$ than $AR = 1$). As Hoerner writes, "...rounded edged result in loss of effective span or aspect ratio." Hoerner also reports that K for an $AR = 3$ monoplane is 0.133 for rounded and 0.123 for square tips.

Monoplane: Velocity Cutplane, AR=1, $\alpha = 5^\circ$

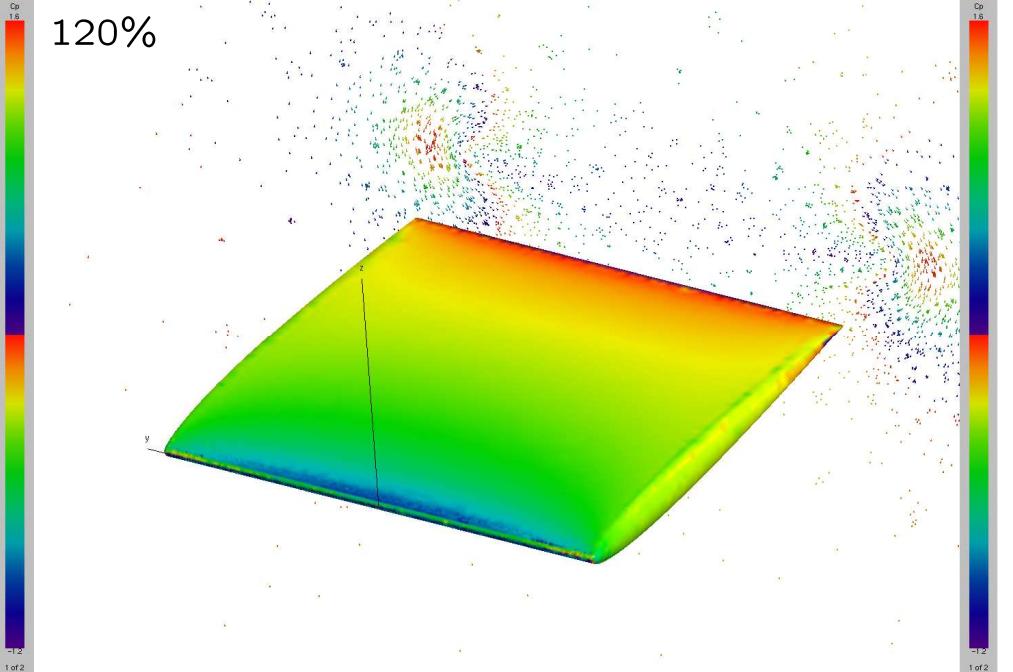
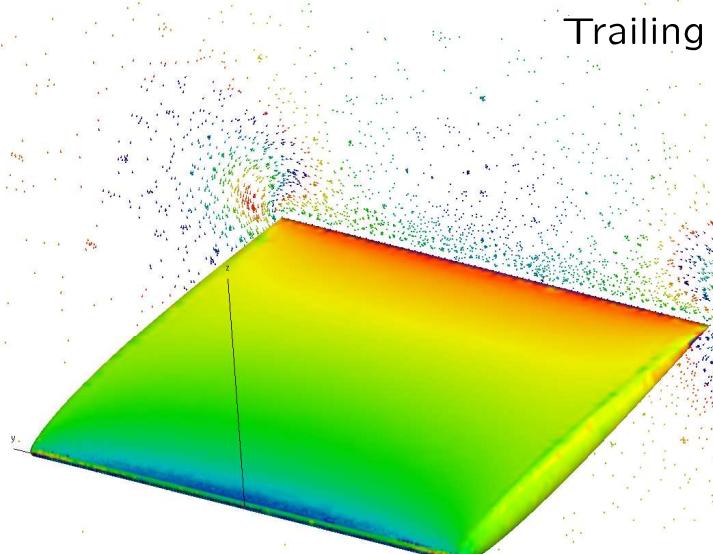
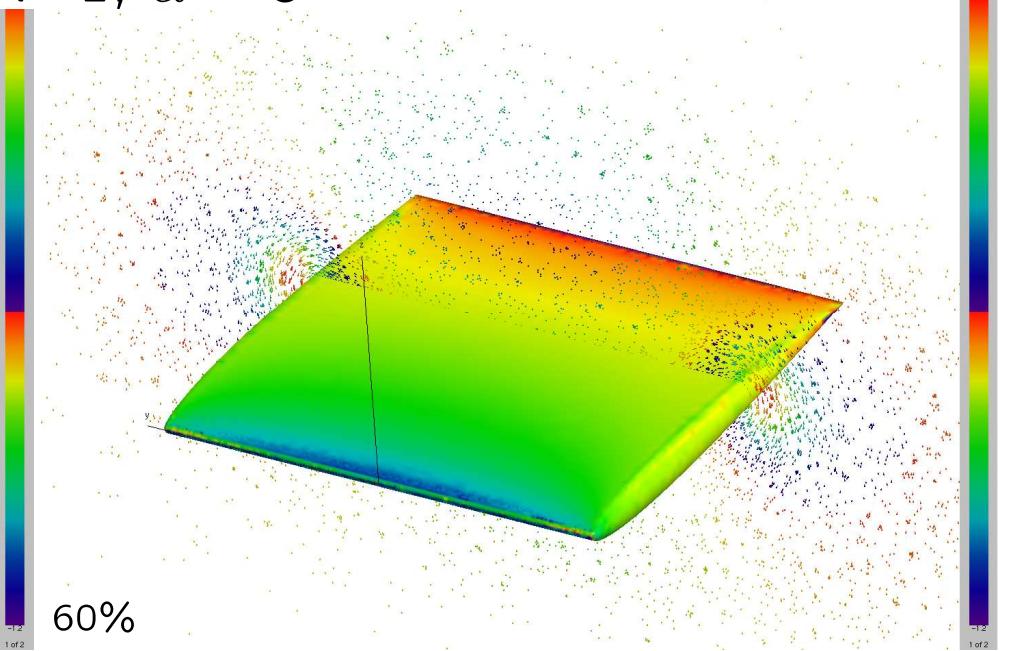


Leading Edge

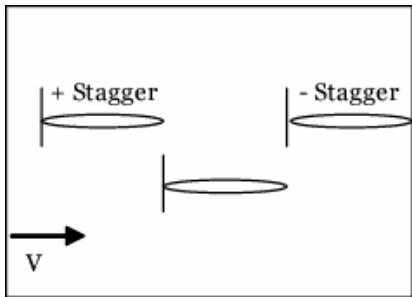
60%

Trailing Edge

120%



Biplane Stagger:



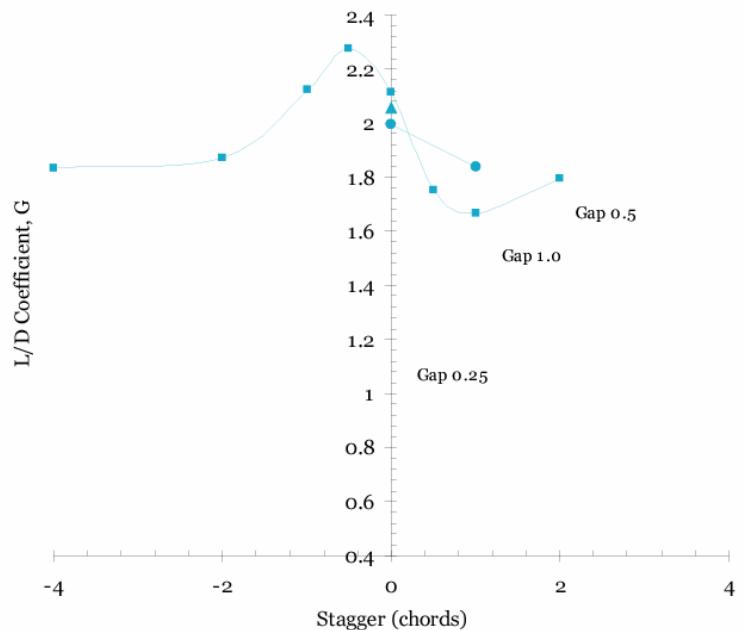
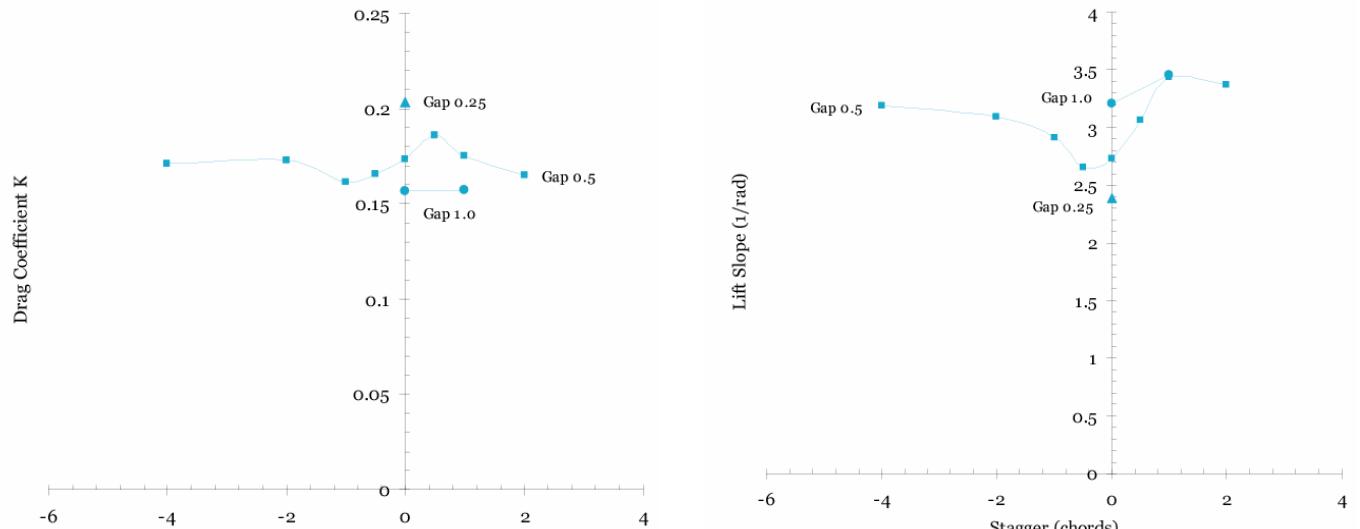
$$\frac{L}{D} = \frac{1}{C_{L\alpha} K \alpha} = \frac{G}{\alpha}$$

Biplane Stagger:

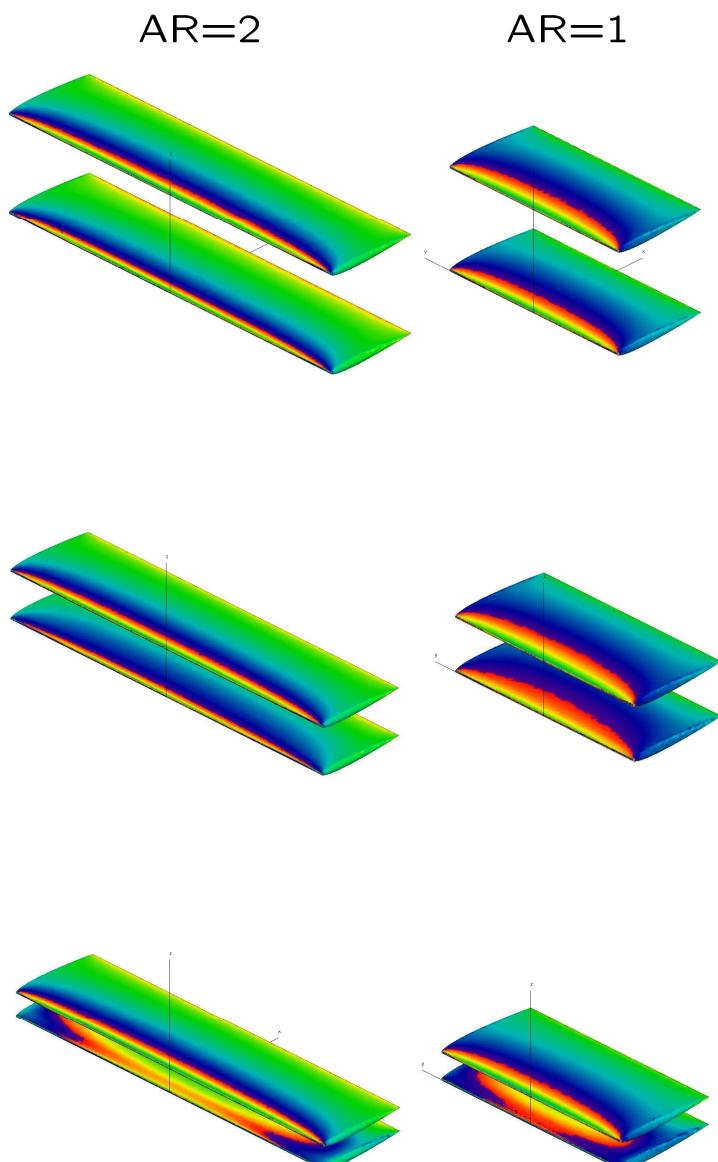
Staggering is common for biplanes. Other than the classic Beech 17, positive stagger (upper wing moved upstream) is usually seen. For $AR = 4$ and a gap of 0.5, an optimal stagger of about -0.5 chord improves L/D by about 8% at the expense of optimal $C_{L\alpha}$.

The lift, drag, and L/D curves exhibit the velocity characteristics of a cutline through vortex: up-down bulges, equal asymptotes at $\pm\infty$, and a decreasing perturbation magnitude with gap distance.

This stagger experiment did not consider or optimize decalage.



Biplane: Surface Pressure C_p at $\alpha = 5^\circ$



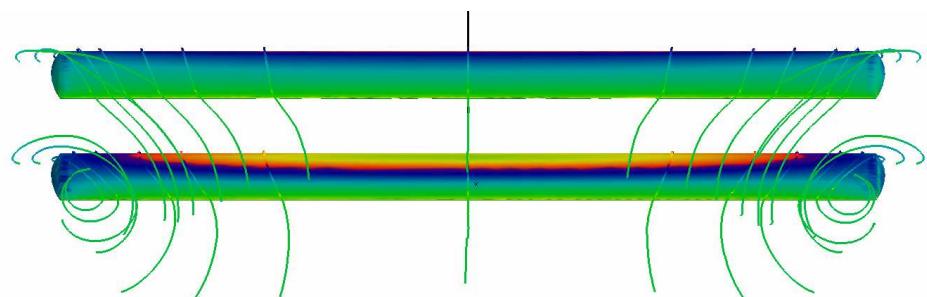
Biplane Gap Spacing:

Flowfield interactions occur between the biplane's wings. As the gap narrows, a lower pressure region forms between the wing sections. A comparison of the upper and lower pressure distributions shows that individual wing surfaces are no longer locally symmetric. Close inspection of the tips shows vortex formation.

This inviscid solution is unable to capture possible low Reynolds number separation bubbles caused by the larger aft-airfoil pressure gradient.

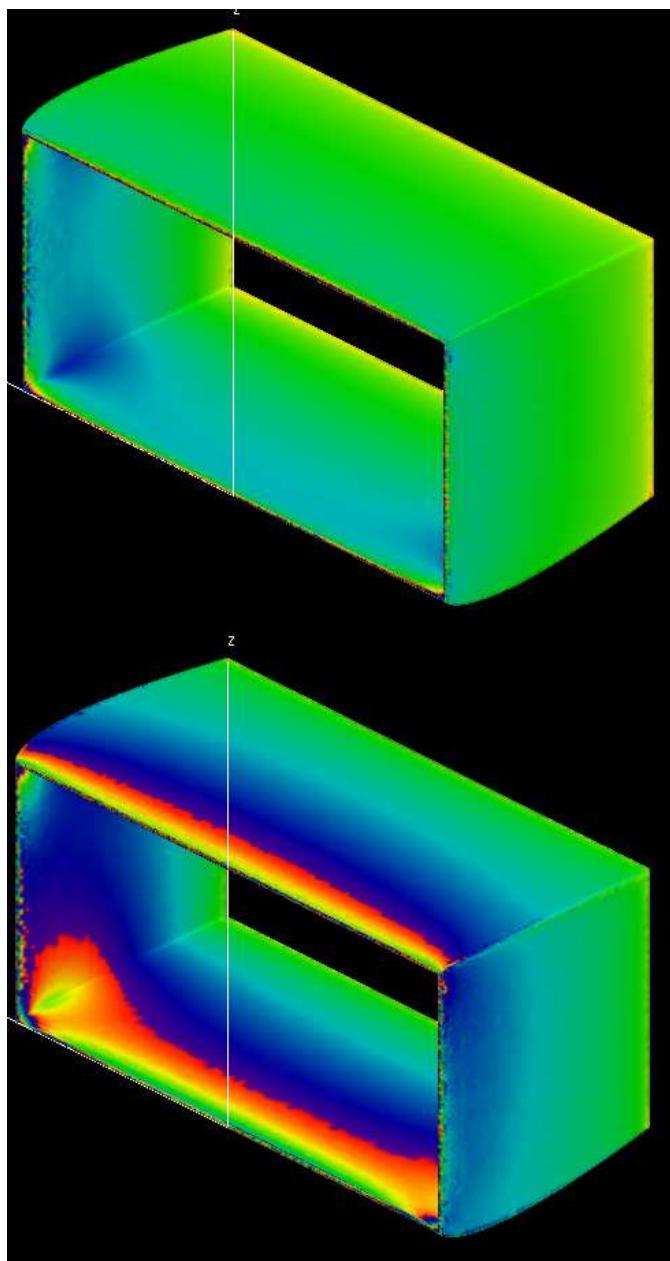
These flowfields also occur with a monoplane in ground effect.

Wake Roll-up (Gap=0.25, $AR=1.0$, $\alpha = 5^\circ$)



Box Biplane

Surface Pressure C_P



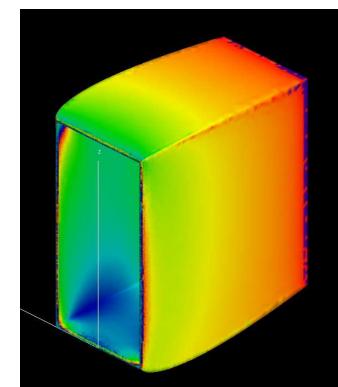
Box Biplane:

The box biplane's geometry consists of the previous biplane geometry with a NACA 0009 connecting endplate. A box biplane version with thinner (2% rather than 9%) endplates gave almost identical performance.

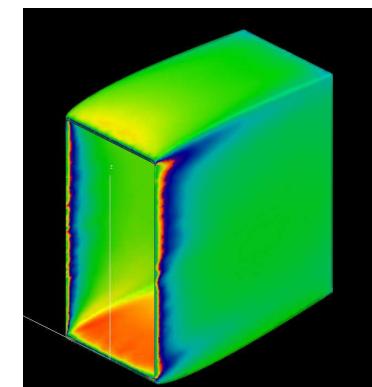
Box Biplane:

The endplate does however form an interference effect at the inside intersection of the plate and the wing panel. Both images ($\alpha = 0$ and $\alpha = 5$) display this lower C_P (higher velocity) region. The interference region for the thin-endplate version reduces the *inner* spanwise variation in C_P to near zero. See the $AR = 0.5$ images below for the surface velocity difference between 2% and 9% endplates.

9% Endplate



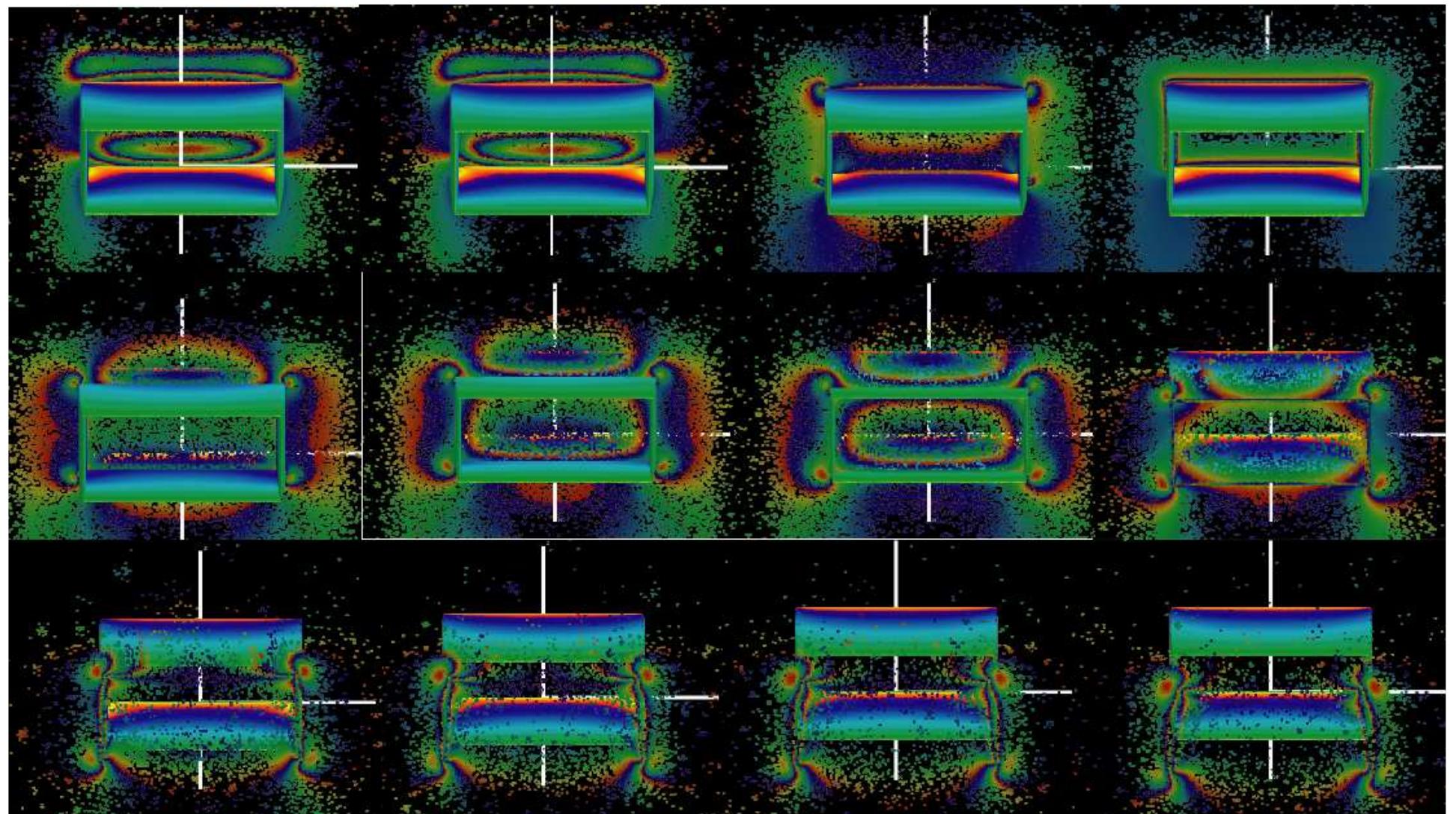
1.8% Endplate



Box Biplane at $\alpha = 5^\circ$

Spanwise Velocity Cutplanes at chord positions:

-20%, 0%, 20%, 40%, 60%, 80%, 100%, 120%,
140%, 160%, 180%, 200%

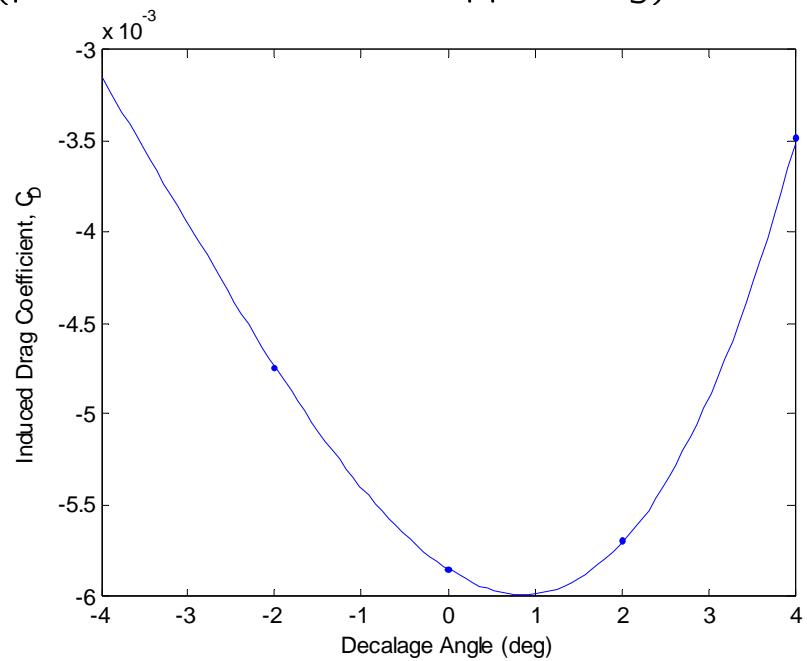


Biplane: Decalage

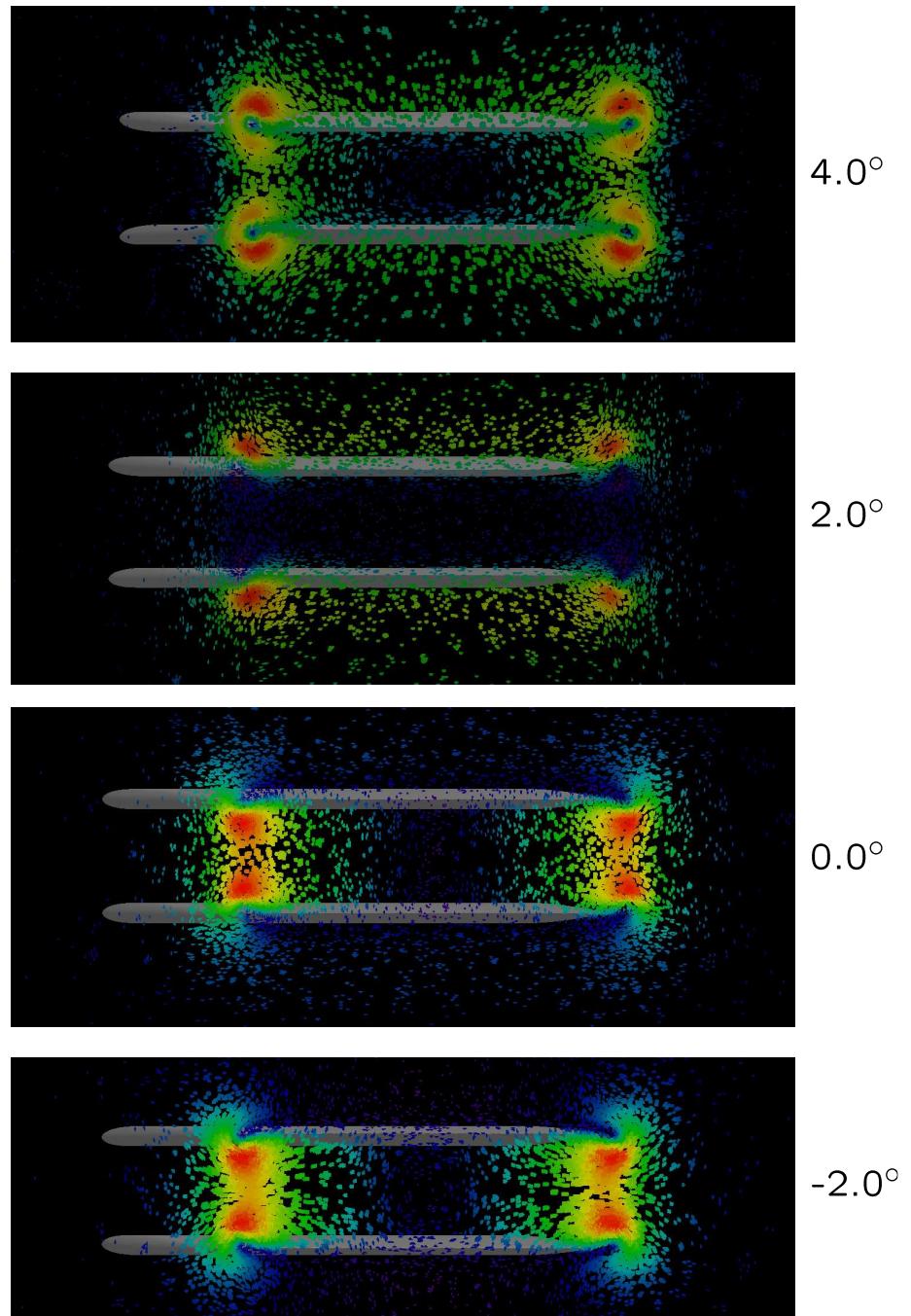
Biplane Decalage:

Decalage is common for biplanes. Positive decalage, the most common, increases the upper wing's incidence angle and decreases the lower wing's incidence angle.

For this $AR = 2$ experiment, C_{D_i} versus decalage angle has a minimum at about +1 degree and is not symmetric. Trailing edge and vortex spacing likely produces the asymmetry. For a decalage angle greater than approximately 1°, the trailing edge tip flow is from inside around to the outside (positive circulation on upper wing).



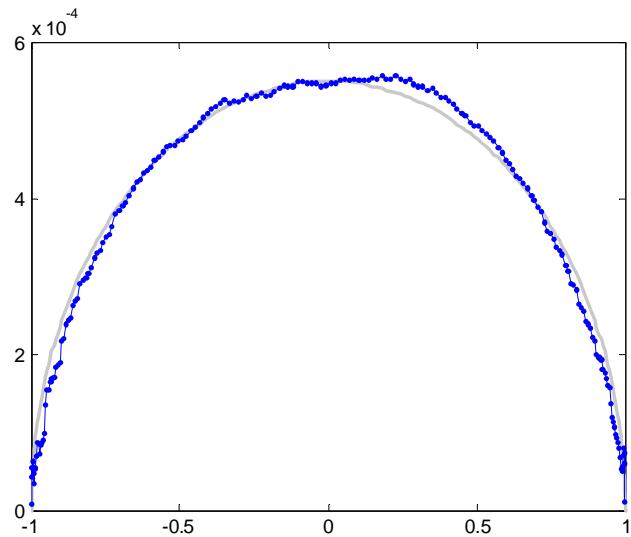
Velocity Cutplane at 120% chord



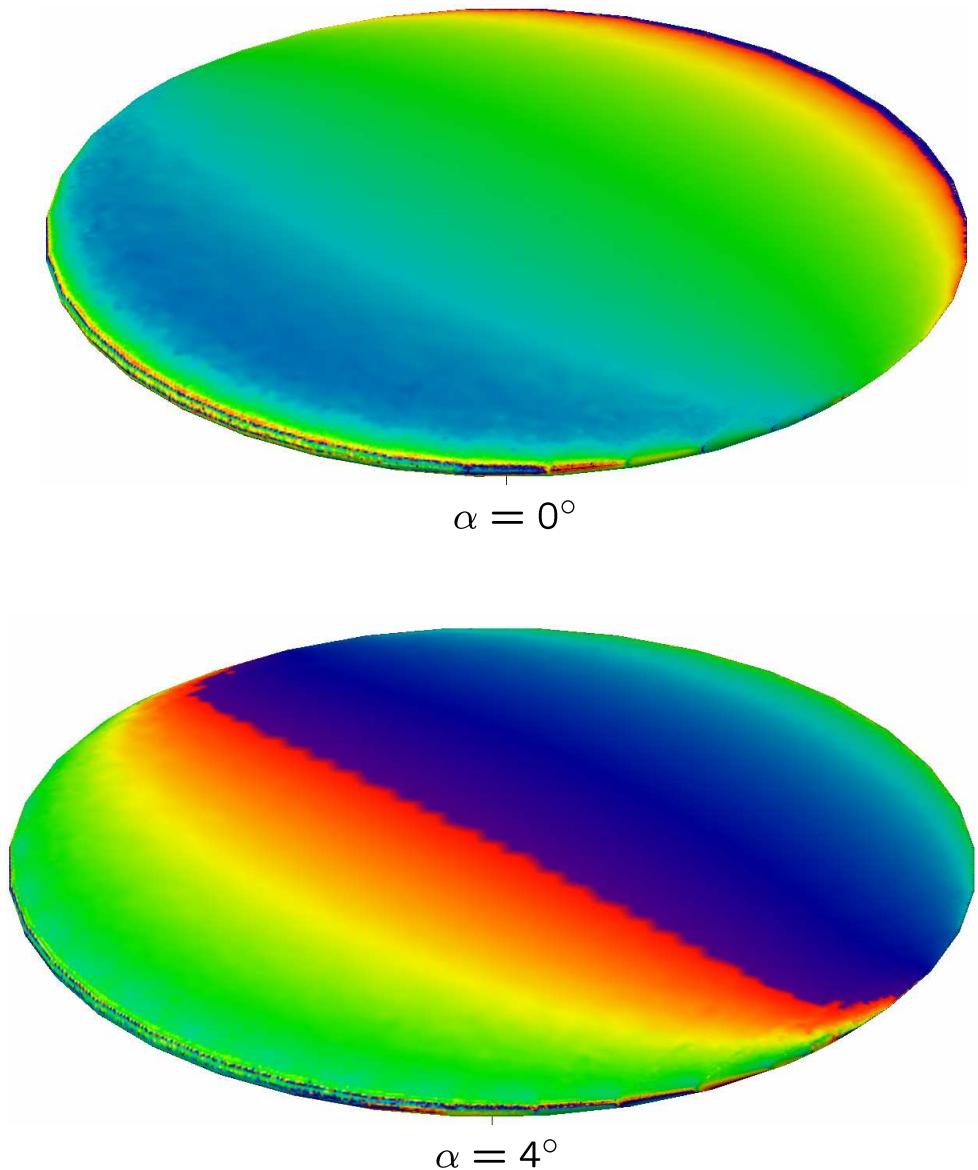
Circle

The circle geometry is an elliptical wing of equal span and chord. The following figure gives an $\alpha = 5^\circ$ sectional lift distribution (spanwise smoothed) versus an ideal elliptical distribution of the same magnitude.

Sectional Lift:



Careful inspection of the surface pressure distribution shows the discrete ribs (and linear interpolation) forming the circle's geometry. The solution grid could use some refinement.



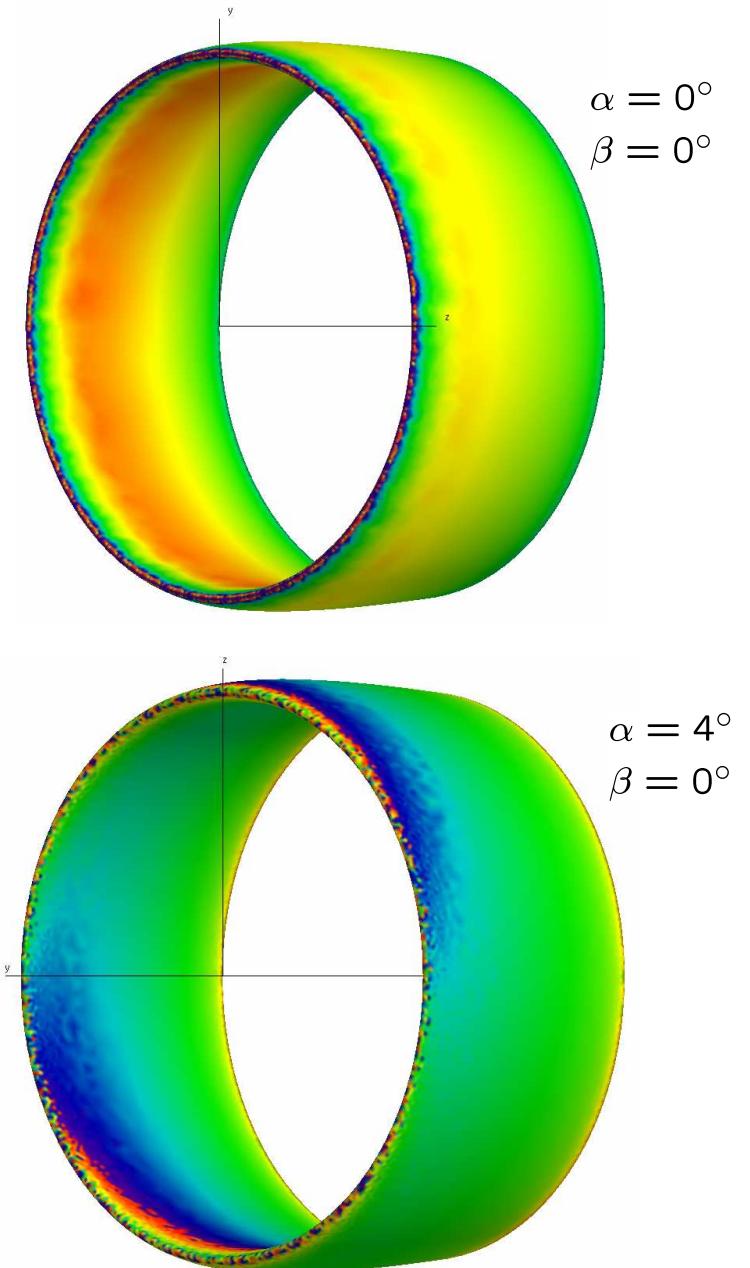
Cowl

Having elliptical surface normals, the cowl behaves as an elliptical biplane wing. Viscous drag, with the ring's extra surface area, would not be identical to an elliptical wing.

For $\alpha = 0$, the internal surface pressure's magnitude is larger than the external surface pressure. For $\alpha = 5^\circ$, the inner pressure distribution encroaches into the upper hemicircle further than the outside encroaches into the lower hemicircle.

Incidently, these inner characteristics partially explain the large performance variances typically seen in certain ducted fan designs.

Hoerner's fluid dynamics book gives an interesting review of 'Ring Foil' performance characteristics.



Raw Data Values

	b	AR	S Gap	Stagger	alpha Deg	alpha Rad	Fx	Fy	Fz	L	D	Cl	Cd	Cla	k		
Monoplane																	
wing 1	4	4	4		0	0	-0.02540	0.00011	-0.00155	-0.00155	-0.02540	-0.00038	-0.00622	#DIV/0!	0		
	4	4	4		5	0.08726646	-0.08903	-0.00016	1.39406	1.39651	0.03261	0.34180	0.00803	3.916691	0.121951		
	4	4	4		10	0.17453293	-0.27612	-0.00051	2.78174	2.78742	0.21112	0.68222	0.05167	3.908845	0.124378		
wing 1	2	2	2		0	0	-0.01211	0.00011	-0.00179	-0.00179	-0.01211	-0.00087	-0.00593	#DIV/0!	0		
	2	2	2		5	0.08726646	-0.03195	-0.00025	0.49966	0.50054	0.01172	0.24502	0.00574	2.807667	0.194317		
	2	2	2		10	0.17453293	-0.08979	-0.00070	1.01075	1.01099	0.08709	0.49488	0.04263	2.835443	0.19827		
wing1	1	1	1		-5	-0.08726646	-0.01237	0.00019	-0.16345	-0.16391	0.00192	-0.16046	0.00188	1.838787	0.328043		
	1	1	1		0	0	-0.00671	-0.00010	-0.00077	-0.00077	-0.00671	-0.00075	-0.00657	#DIV/0!	0		
	1	1	1		5	0.08726646	-0.01149	-0.00032	0.16226	0.16265	0.00270	0.15923	0.00264	1.824668	0.363181		
wing20	0.5	0.5	0.5		0	0				0.00000	0.00000						
	0.5	0.5	0.5		0	0	-0.00249	0.00001	0.00013	0.00013	-0.00249	0.00025	-0.00488	#DIV/0!	0		
	0.5	0.5	0.5		5	0.08726646	-0.00379	-0.00006	0.04735	0.04810	0.00040	0.09418	0.00079	1.079177	0.639338		
	0.5	0.5	0.5		20	0.34906585	-0.02265	-0.00054	0.21970	0.21420	0.05386	0.41940	0.10545	1.201491	0.627271		
Monoplane Endplates																	
wing23	0.5	0.5	0.5		0	0	-0.00071	-0.00024	0.00594	0.00594	-0.00071	0.01163	-0.00138	#DIV/0!	0		
	0.5	0.5	0.5		5	0.08726646	-0.00269	0.00000	0.06457	0.06456	0.00295	0.12641	0.00578	1.448587	0.448423		
	0.5	0.5	0.5		10	0.17453293	-0.08946	0.00000	0.12759	0.12712	0.01383	0.24890	0.02708	1.426075	0.459443		
Biplane																	
Gap 1																	
wing2	4	2	8	1	0	0	-0.05630	0.00010	-0.00132	-0.00132	-0.05630	-0.00016	-0.00688	#DIV/0!	0		
	4	2	8	1	0	5	0.08726646	-0.15556	0.00004	2.27949	2.28437	0.04370	0.27955	0.00535	3.203405	0.158595	
	4	2	8	1	0	10	0.17453293			0.00000	0.00000	0.00000	0.00000	0	#DIV/0!		
wing5	2	1	4	1	0	0	0	-0.02574	-0.00002	-0.00047	-0.00047	-0.02574	-0.00012	-0.00630	#DIV/0!	0	
	2	1	4	1	0	5	0.08726646	-0.05793	0.00080	0.83660	0.83847	0.01520	0.20521	0.00372	2.35159	0.237943	
	2	1	4	1	0	10	0.17453293			0.00000	0.00000	0.00000	0.00000	0	#DIV/0!		
wing15	1	0.5	2	1	0	0	0	-0.01254	0.00000	0.00113	0.00113	-0.01254	0.00055	-0.00614	#DIV/0!	0	
	1	0.5	2	1	0	5	0.08726646	-0.02181	0.00000	0.28948	0.29028	0.00350	0.14209	0.00171	1.62823	0.388928	
	1	0.5	2	1	0	10	0.17453293	-0.04977	0.00000	0.58807	0.58777	0.05310	0.28771	0.02599	1.648485	0.388181	
wing18	0.5	0.25	1	1	0	0	0	-0.00525	0.00002	-0.00038	-0.00038	-0.00525	-0.00037	-0.00514	#DIV/0!	0	
	0.5	0.25	1	1	0	5	0.08726646	-0.00775	0.00004	0.09281	0.09314	0.00037	0.08118	0.00036	1.044641	0.662232	
	0.5	0.25	1	1	0	10	0.17453293	-0.01539	0.00001	0.19254	0.19226	0.01828	0.18825	0.01790	1.078568	0.650128	
Biplane																	
Gap 0.5																	
wing 3	4	2	8	0.5	0	0	0	-0.04779	0.00014	-0.00319	-0.00319	-0.04779	-0.00039	-0.00585	#DIV/0!	0	
	4	2	8	0.5	0	5	0.08726646	-0.13719	0.00023	1.94188	1.94642	0.03257	0.23819	0.00399	2.729498	0.173351	
wing 6	2	1	4	0.5	0	0	0	0	-0.02392	0.00000	-0.00286	-0.00286	-0.02392	-0.00070	-0.00585	#DIV/0!	0
	2	1	4	0.5	0	5	0.08726646	-0.05014	0.00000	0.71261	0.71427	0.01216	0.17482	0.00288	2.003258	0.288885	
	2	1	4	0.5	0	10	0.17453293			0.00000	0.00000	0.00000	0.00000	0	#DIV/0!		
wing17	1	0.5	2	0.5	0	0	0	-0.01215	-0.00020	-0.00015	-0.00015	-0.01215	-0.00007	-0.00595	#DIV/0!	0	
	1	0.5	2	0.5	0	5	0.08726646	-0.02015	0.00000	0.25031	0.25112	0.00174	0.12292	0.00085	1.408583	0.450241	
	1	0.5	2	0.5	0	10	0.17453293			0.00000	0.00000	0.00000	0.00000	0	#DIV/0!		
Biplane																	
Gap 0.25																	
wing 4	4	2	8	0.25	0	0	0	-0.03607	0.00000	-0.00302	-0.00302	-0.03607	-0.00037	-0.00441	#DIV/0!	0	
	4	2	8	0.25	0	5	0.08726646	-0.11241	0.00000	1.68655	1.70188	0.03605	0.20827	0.00441	2.386576	0.203477	
wing 7	2	1	4	0.25	0	0	0	-0.01651	0.00000	-0.53383	-0.53383	-0.01651	-0.13065	-0.00404	#DIV/0!	0	
	2	1	4	0.25	0	5	0.08726646	-0.03923	0.00000	0.61668	0.61774	0.01466	0.15119	0.00359	1.732518	0.333723	

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