Drag Estimation of Military Aircraft

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Drag Polar

All types of drag can be approximated by

$$C_D = C_{D_o} + k_1 C_L{}^2 + k_2 C_L$$

Where

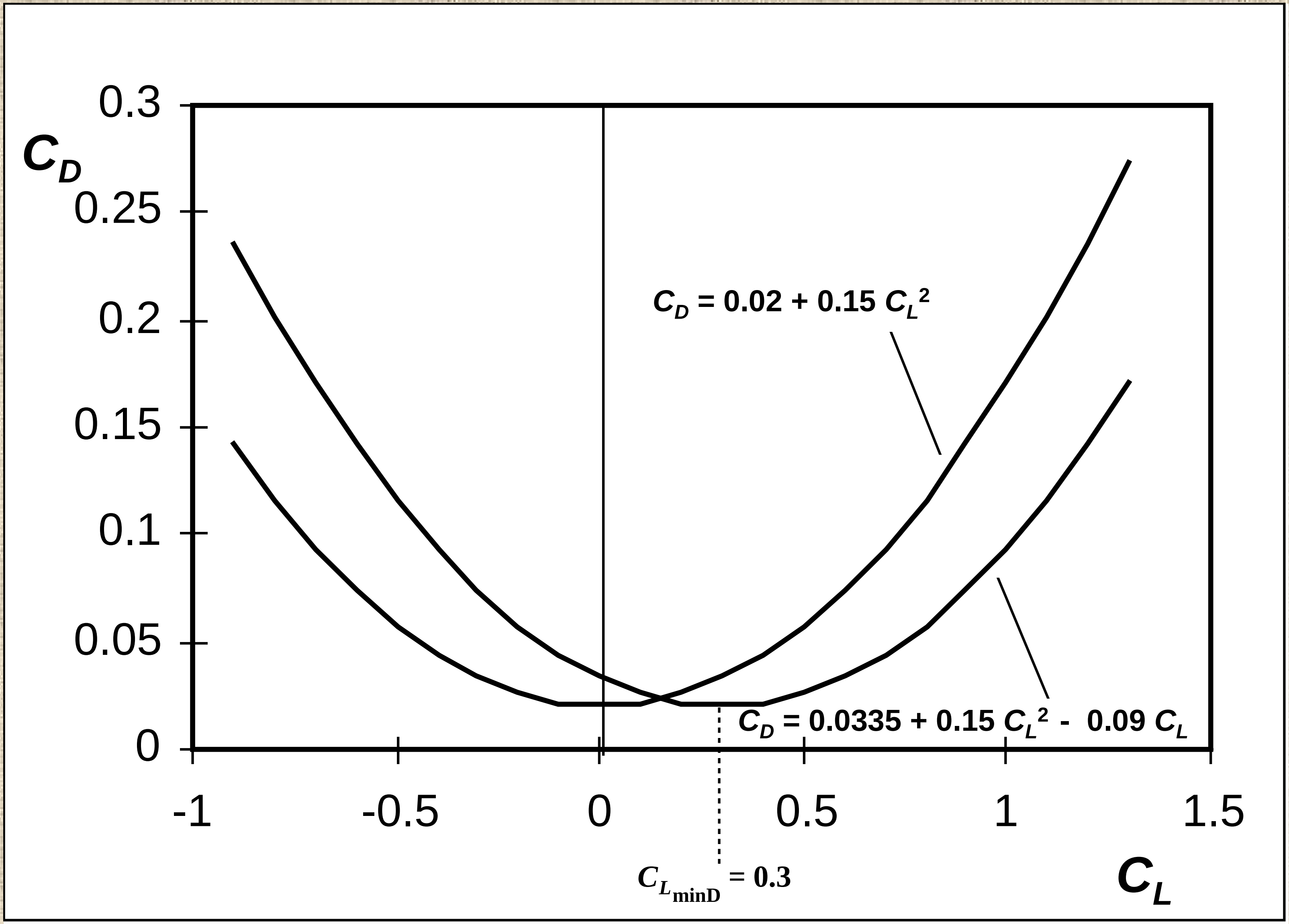
$k_1 = 1/(pi\ e_o AR)$

$$k_2 = -2\,k_1\,C_{L_{minD}}$$

k_2 is chosen to allow modeling of wings with airfoils which generate minimum drag at some non-zero value of lift.

C_{LminD} is the lift coefficient at which the minimum drag coefficient for an aircraft occurs

Example



0.3
C_D
0.25
0.2
0.15
0.1
0.05
0
$C_D = 0.02 + 0.15\ C_L^2$
$C_D = 0.0335 + 0.15\ C_L^2 - 0.09\ C_L$
-1
-0.5
0
0.5
1
1.5
$C_{L_{\text{minD}}} = 0.3$
C_L

Drag Polar Estimation

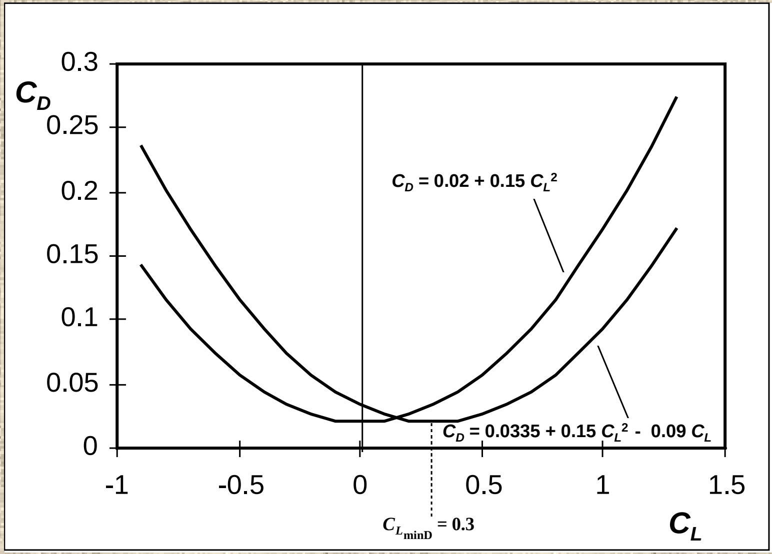
Determining C_{LminD} : two ways

- by plotting the drag polar for the wing using actual airfoil data

- assume that the airfoil generates minimum drag when it is at zero angle of attack, and that the effect of induced drag is to move C_{LminD} to a value halfway between zero and the value of C_L when $\alpha = 0$.

$$C_{L_{\alpha=0}} = C_{L_\alpha}(\alpha_a) = C_{L_\alpha}(-\alpha_{L=0})$$

$$C_{L_{minD}} = C_{L_\alpha}\left(\frac{-\alpha_{L=0}}{2}\right)$$



- aircraft's zero-lift drag coefficient

$$C_{D_o} = C_{D_{min}} + k_1 C_{L_{minD}}^{\;2}$$

Parasite Drag Coefficient

-> Estimating wetted area, two ways

-computer-aided drafting (CAD)

-By approximating the aircraft as a set of simple shapes

-> equivalent skin friction drag coefficient, C_{fe}

$$C_{f_e} = C_{D_o} \frac{S}{S_{wet}}$$

$$C_{D_{min}} = C_{f_e} \frac{S_{wet}}{S}$$

Common C_{fe} Values

Type	C_{fe}
Jet Bomber and Civil Transport	0.0030
Military Jet Transport	0.0035
Air Force Jet Fighter	0.0035
Carrier-Based Navy Jet Fighter	0.0040
Supersonic Cruise Aircraft	0.0025
Light Single Propeller Aircraft	0.0055
Light Twin Propeller Aircraft	0.0045
Propeller Seaplane	0.0065
Jet Seaplane	0.0040

Induced Drag Coefficient

-> Oswald's Efficiency Factor, e_o

$$e_o = 4.61(1 - 0.045 AR^{0.68})(\cos\Lambda_{LE})^{0.15} - 3.1$$

-> $k_1 = 1/(\pi e_o AR)$

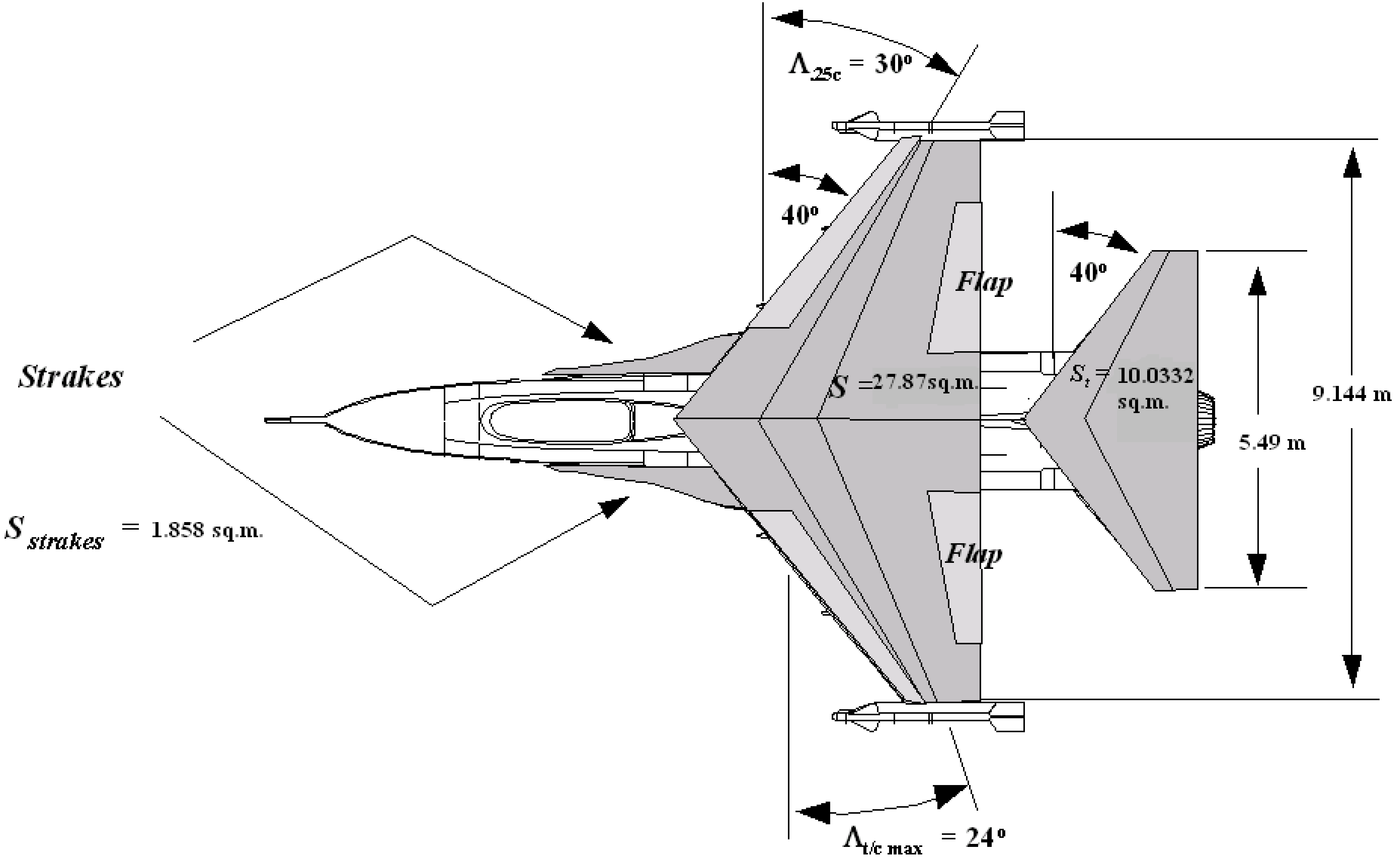
-> $C_D = C_{Do} + k_1 C_L^2$

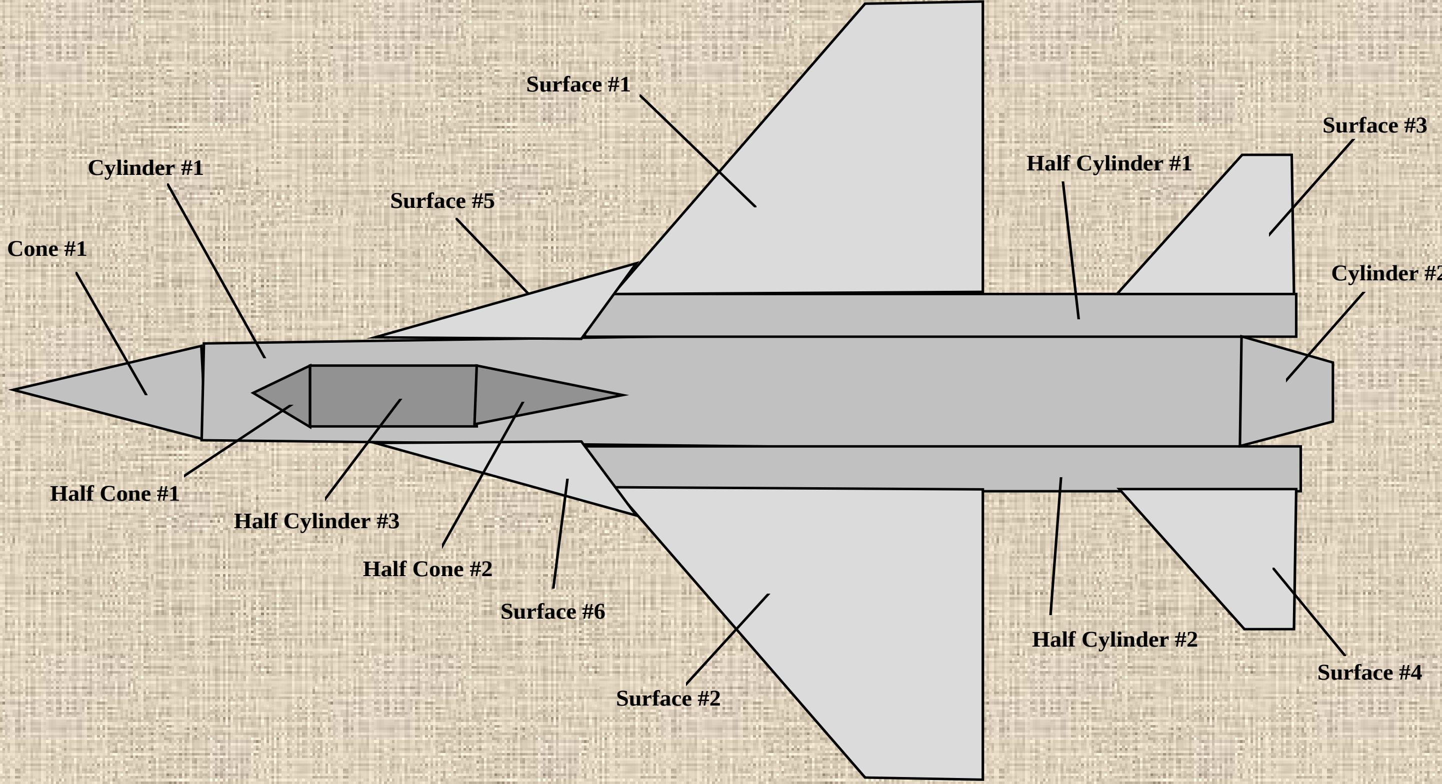
Example of
Drag & Lift Coefficient estimation

F-16 Fighting Falcon aircraft

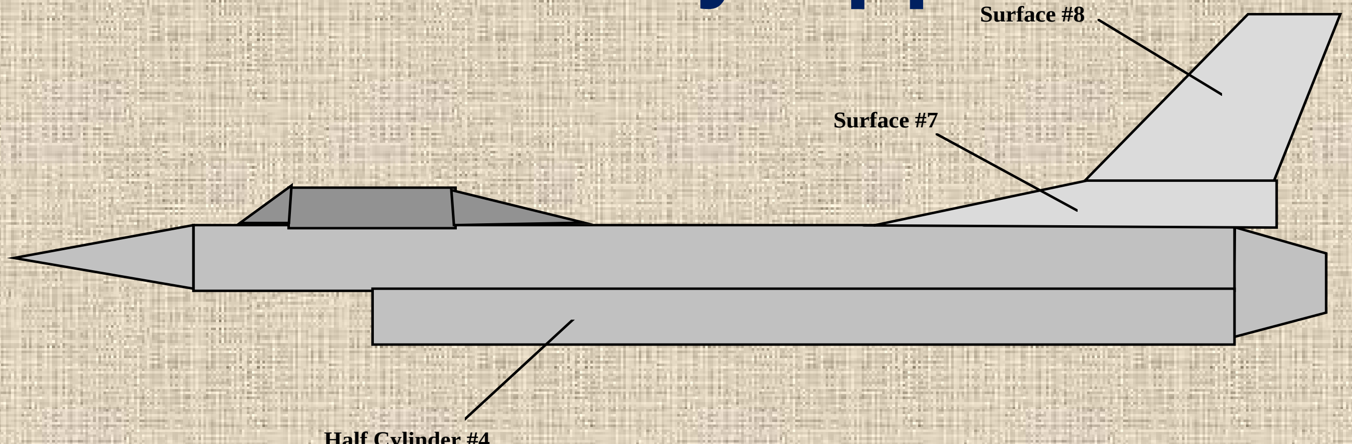
F-16 THREE VIEW DIAGRAM

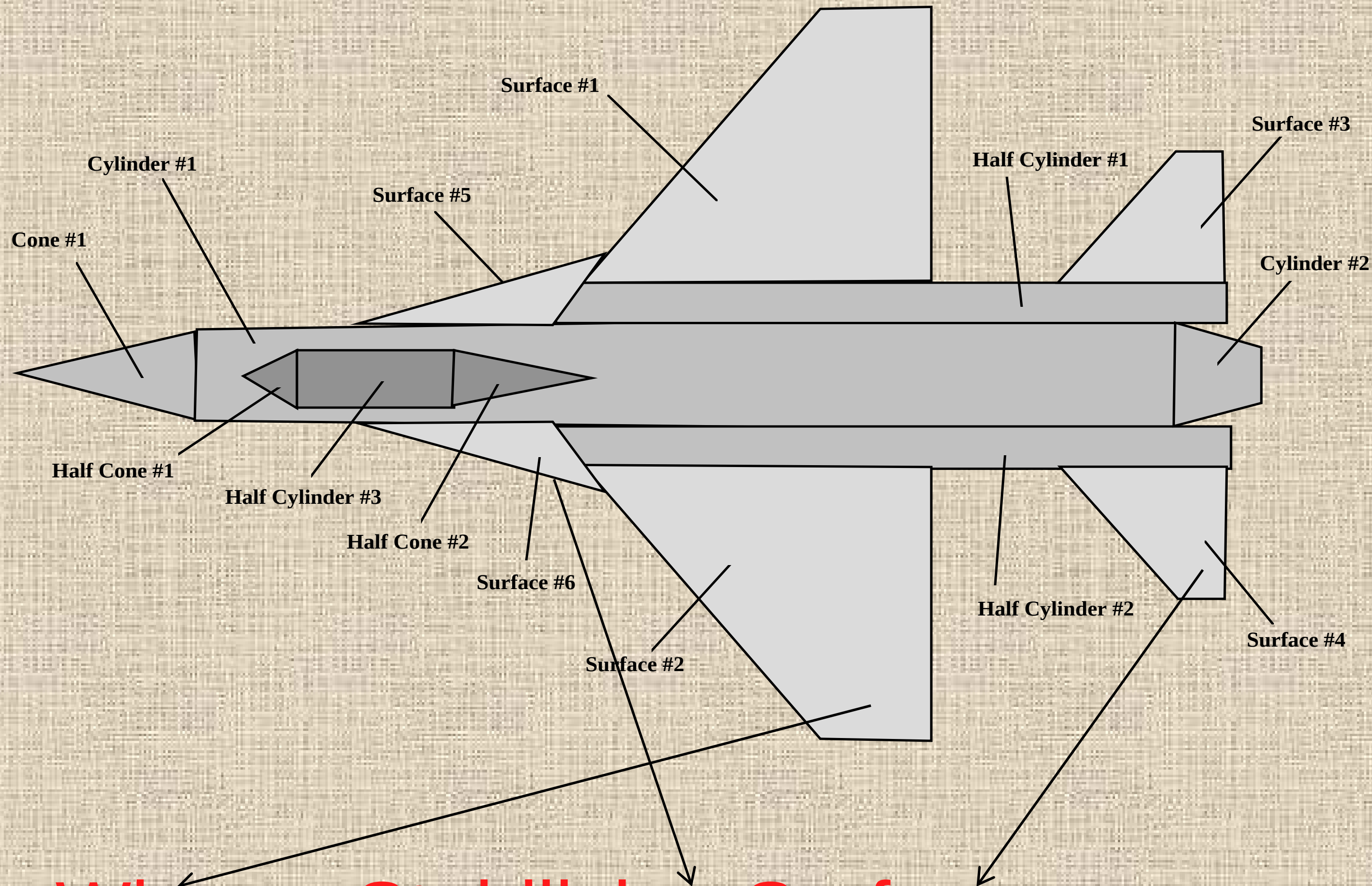
F-16 Aircraft Geometry





F-16 Geometry Approximated



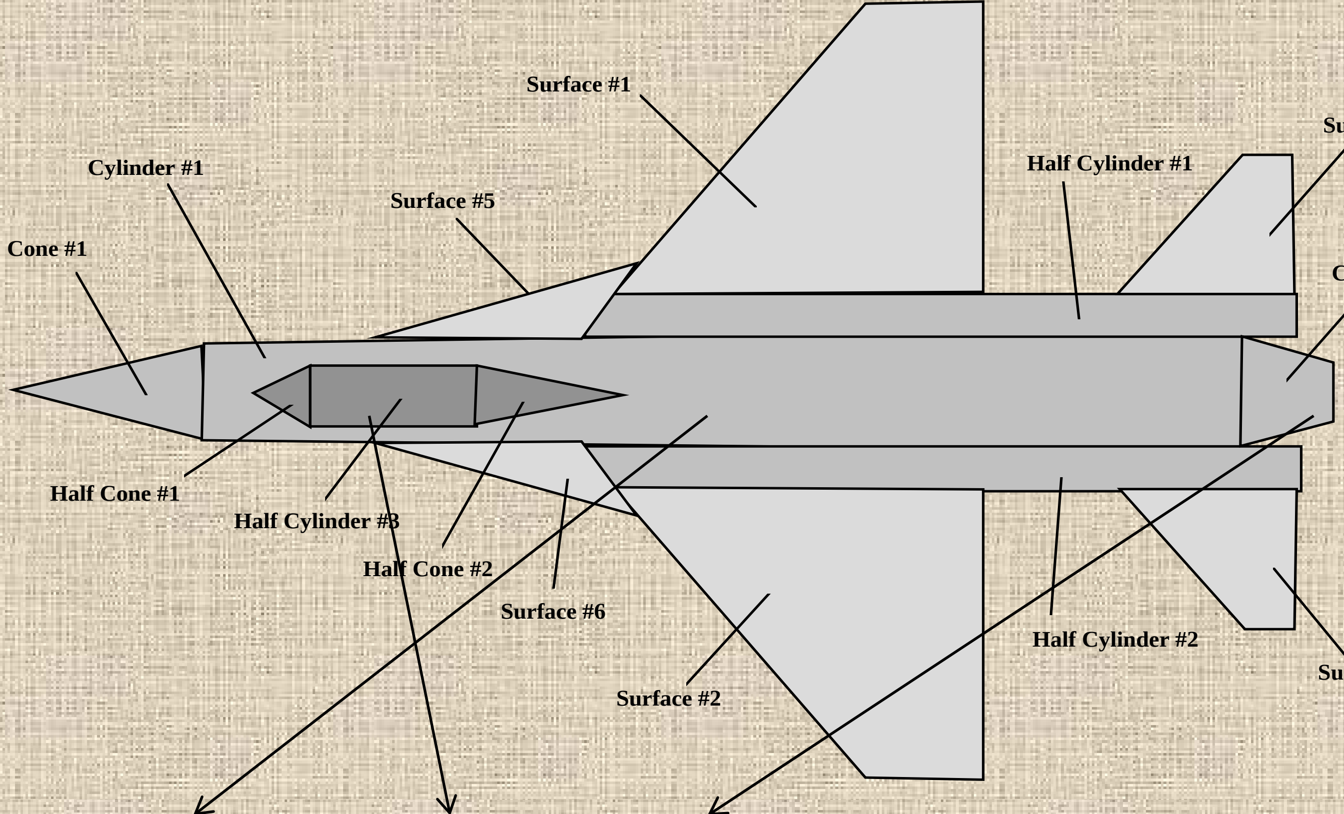


1) Wing or Stabilizing Surfaces:

$$S_{exposed} = 0.5^* \left(b^*(C_{tip}+C_{root})\right)$$

$$S_{wet} = S_{exposed} \left[1.977 + 0.52(t/c)\right]$$

Eqn. 1



- Fuselage, Canopy, Nozzle

$$S_{wet} = \pi\, l \left(\frac{h+w}{2}\right) \quad \text{; for elliptical cross sections}$$

$$S_{wet} = 2\, l\,(h+w) \quad \text{; for rectangular cross sections}$$

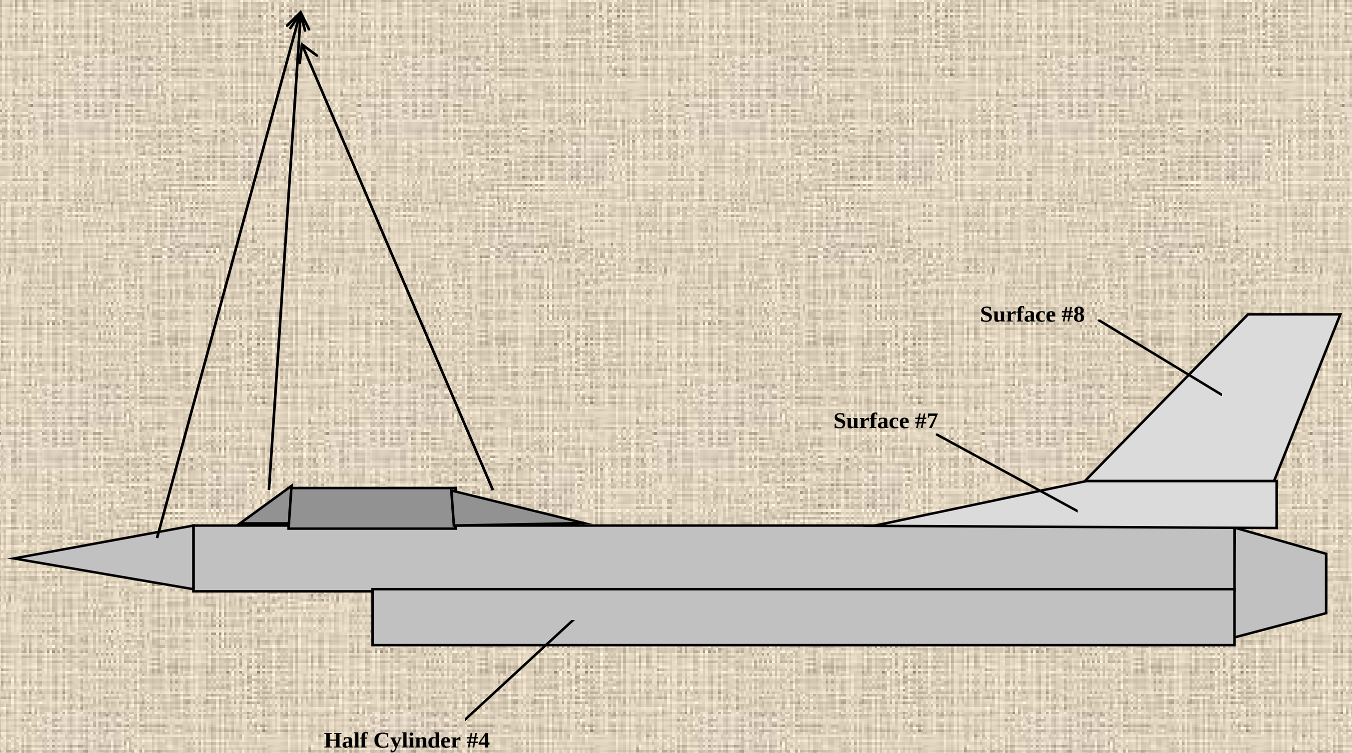
Eqn. 2

Nose, Front and rear part of canopy

$$S_{wet} = \pi \, l \left(\frac{h_1 + w_1 + h_2 + w_2}{4} \right) \quad \text{; for elliptical and circular cross sections}$$

$$S_{wet} = l \, (h_1 + w_1 + h_2 + w_2) \quad \text{; for rectangular cross sections}$$

Eqn. 3



	Surface	Span, (m)	C_{root}, (m)	C_{tip}, (m)	T_{max}/C		Equation	S_{wet}, (m^2)	$S_{Interaction}$, (m^2)	Net S_{wet}, (m^2)
Wing	1 & 2	3.66	4.27	1.07	0.04		(1)	39.05	0.00	39.05
Horizontal Tail	3 & 4	1.83	2.38	0.61	0.04		(1)	10.93	0.00	10.93
Strakes	5 & 6	0.61	2.93	0	0.06		(1)	3.59	0.00	3.59
Vertical Tail	7	0.43	3.81	1.83	0.1		(1)	2.46	0.00	2.46
Vertical Tail	8	2.13	2.44	0.91	0.06		(1)	7.16	0.00	7.16
	9 & 10	0.46	1.52	0.91	0.03		(1)	2.23	0.00	2.23
	Cylinder	**Length, (m)**	**Height, (m)**	**Width, (m)**						
Fuselage	1	11.89	0.76	1.52			(2)	54.22	0.00	54.22
	Cone	**Length, (m)**	**Height, (m)**	**Width, (m)**	**H_2, (m)**	**W_2, (m)**				
Nose	1	1.83	0.76	1.52	0	0	(3)	3.28	0.00	3.28
Nozzle	2	1.22	1.83	1.83	1.22	1.22	(3)	5.84	0.00	5.84
	Half-Cylinder	**Length, (m)**	**Height, (m)**	**Width, (m)**						
Fuselage Sides	1 & 2	7.32	0.24	0.305			50% of (2)	6.27	3.51	2.76
Canopy	3	1.52	0.61	0.61			50% of (2)	1.46	0.93	0.53
Fuselage Bottom	4	9.14	0.76	1.52			50% of (2)	20.84	13.89	6.95
	Half-Cone	**Length, (m)**	**Height, (m)**	**Width, (m)**						
Canopy	1	0.61	0.61	0.61			50% of (3)	0.29	0.19	0.10
Canopy	2	1.22	0.61	0.61			50% of (3)	0.58	0.37	0.21
									Total S_{wet}	**139.31**

F-16

- Oswald's Efficiency Factor

$$e_o = 4.61(1 - 0.045AR^{0.68})(\cos L_{LE})^{0.15} - 3.1 = 0.9086$$

$$k_1 = 1/(\pi e_o AR) = 0.117$$

- The F-16's average chord is

$$\overline{c} = b/AR = 9.144m/3 = 3.048m$$

- For standard sea level conditions and $M = 0.2$

$$Re = \rho V\overline{c}/\mu = (1.225 kg/m^3)(0.2 * 340.2 m/s)(3.048m)/(17.893 * 10^{-6} kg/m\ s) = 14,200,000$$

F-16

F-16 Wing Alone Drag Coefficient Variation

C_L	c_d	$k_1 C_L^2$	$C_D = c_d + k_1 C_L^2$
-0.2	.0062	.0047	.0109
-0.1	.006	.0012	.0072
0.0	.0053	0	.0053
0.1	.0045	.0012	.0057
0.2	.0042	.0047	.0089

- $C_{LminD} = 0.04$

- **Assuming:** aircraft's minimum drag is at approximately the same C_L where the wing alone has its minimum drag

$$C_{D_o} = C_{D_{min}} + k_1 C_{L_{minD}}^2 = 0.0167 + 0.117\,(.04)^2 = .0169$$

F-16

$$k_2 = -2\,k_1\,C_{L_{minD}}$$ = -2 (.117) (.04) = -0.0094

C_D = 0.0169 + .117 $C_L^{\,2}$ - 0.0094 C_L

- Supersonic Drag

$M_{crit\ (unswept)}$ = 1.0 - 0.065 $\left(100\dfrac{t_{max}}{c}\right)^{0.6}$ = 1.0 - 0.065 (4)$^{0.6}$ = 0.85

M_{crit} = 1.0 - cos$^{0.6}$ $L_{0.25c}$ (1.0 - $M_{crit\ (unswept)}$)

= 1.0 - cos$^{0.6}$ 30^{o} (1 - 0.85) = 0.865

$$C_{D_{wave}} = \frac{4.5\pi}{S}\left(\frac{A_{max}}{l}\right)^2 E_{WD}\left(0.74 + 0.37\cos\Lambda_{LE}\right)\left[1 - .3\sqrt{M - M_{C_{D_o}\,max}}\right]$$

F-16

Where

A_{max} = 2.37 m^2 and l = 14.78 m,

$$M_{C_{Do}max} = \frac{1}{\cos^{0.2}\Lambda_{LE}} = \frac{1}{\cos^{0.2} 40^o} = 1.05$$

Mach number	C_{Dwave}
1.05	.0261
1.5	.0213
2.0	.0189

$$k_1 = \frac{AR\left(M^2 - 1\right)}{\left(4\,AR\sqrt{M^2-1}\right) - 2}$$

cos L$_{LE}$

Mach number	k_1
1.05	.128
1.5	.252
2.0	.367

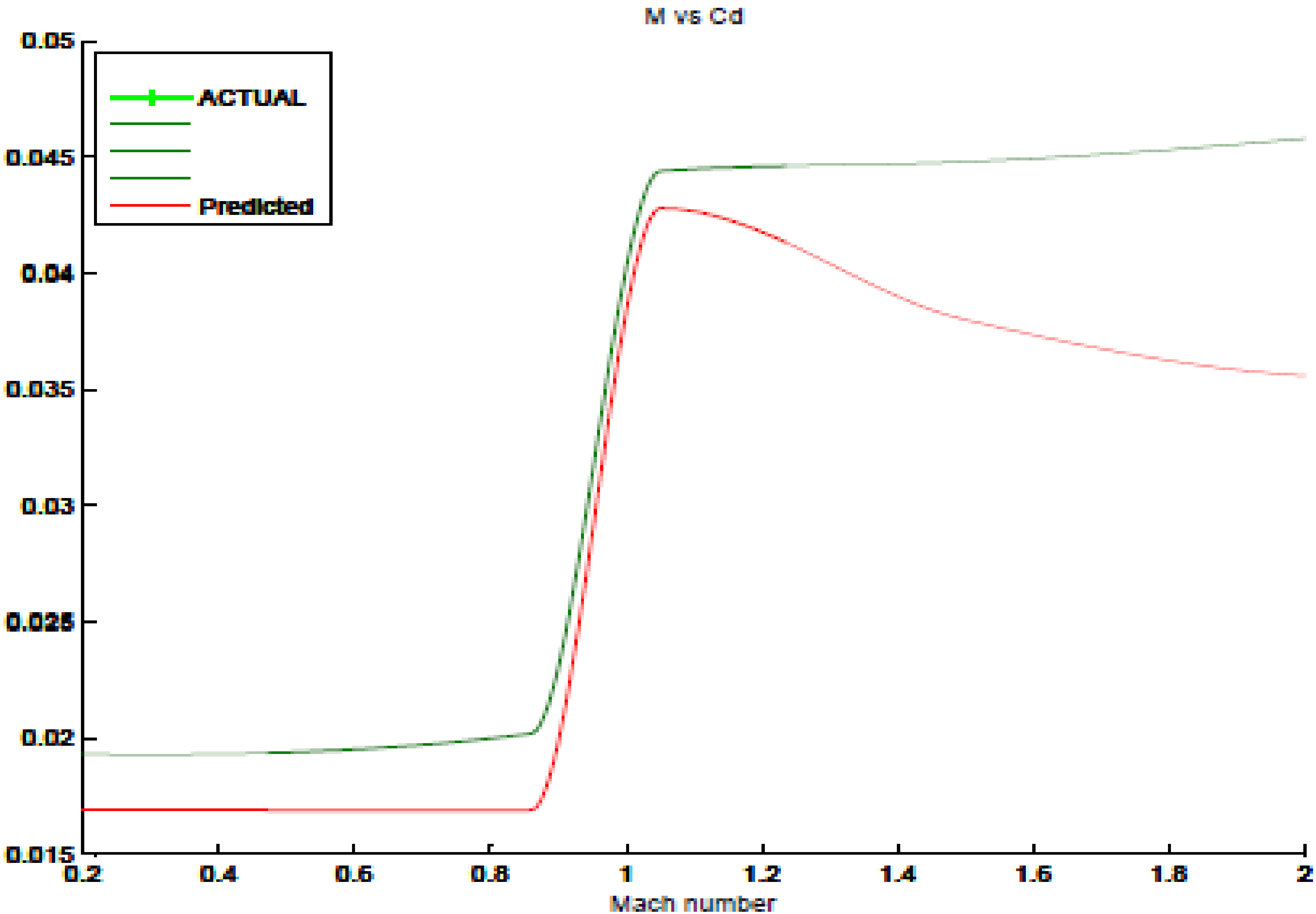
Comparison between Predicted and Actual polar drag

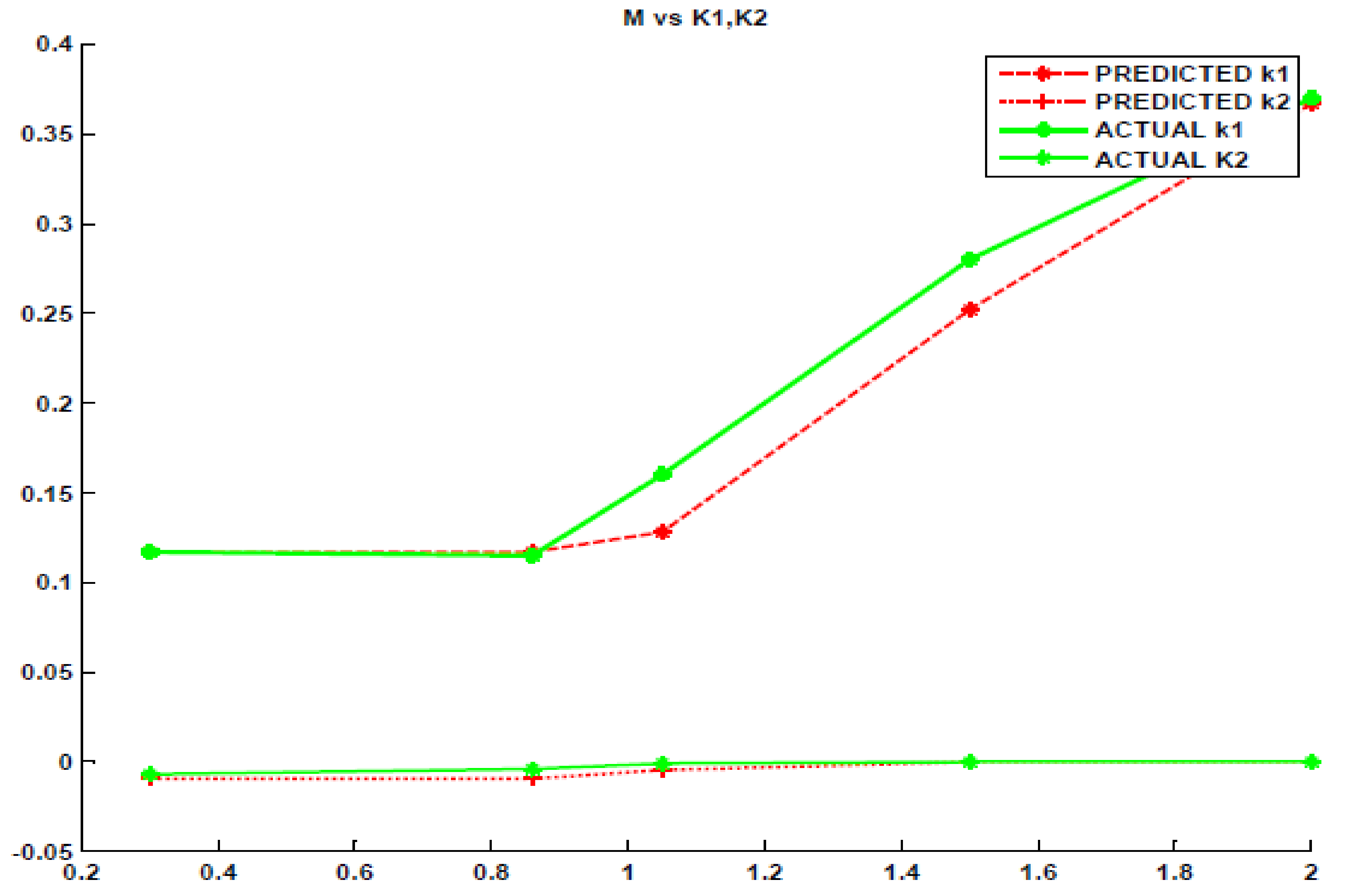
F-16 Drag Polar Predicted

Mach number	C_{Do}	k_1	k_2
0.3	.0169	.117	-.0094
0.86	.0169	.117	-.0094
1.05	.0428	.128	-.0047
1.5	.0380	.252	0
2.0	.0356	.367	0

Actual F-16 Drag Polar

Mach number	C_{Do}	k_1	k_2
0.3	.0193	.117	-.007
0.85	.0202	.115	-.004
1.05	.0444	.160	-.001
1.5	.0448	.280	0
2.0	.0458	.370	0


M vs Cd
ACTUAL
Predicted
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Mach number


M vs K1,K2
PREDICTED k1
PREDICTED k2
ACTUAL k1
ACTUAL K2
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2