Two-Dimensional Aeroelastic Flutter-Onset and Limit Cycle Oscillation Computations for the NASA Benchmark Supercritical Wing Configuration

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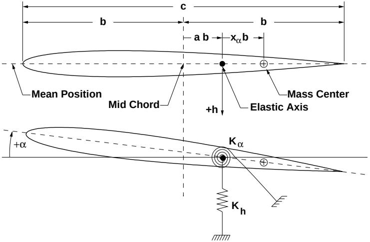
Objectives and Approach

- Objective #1: Can a two-dimensional computational model predict results in the vicinity of the three-dimensional experimental results for the NASA Benchmark Super-critical Wing (BSCW) configuration?
- Objective #2: What sort of predicted aeroelastic Limit Cycle Oscillation (LCO) trends will the two-dimensional computational model yield? i.e., sub-critical or super-critical LCO response?
- Objective #3: Does the two-dimensional computational model predict transonic flow buffet?

- Approach: A nonlinear frequency domain Harmonic Balance (HB) based Computational Fluid Dynamic (CFD) and aeroelastic solver, which allows for the direct computation of aeroelastic LCO response curves.

Airfoil Aeroelastic Configuration Governing Equations

Two-Degree of Freedom Airfoil Model



Governing Equations

$$\mathbf{R}(\mathbf{L}, \mathbf{Q}, \chi) = \mathbf{0}$$

$$\mathbf{L} = \begin{Bmatrix} L_1 \\ L_2 \\ L_3 \\ L_4 \\ L_5 \end{Bmatrix} = \begin{Bmatrix} \bar{\alpha}_0 \\ V \\ \bar{\omega} \\ \mathrm{Re}\left(\dfrac{\bar{h}_1}{\bar{\alpha}_1 b}\right) \\ \mathrm{Im}\left(\dfrac{\bar{h}_1}{\bar{\alpha}_1 b}\right) \end{Bmatrix}, \qquad \mathbf{R} = \begin{Bmatrix} R_1 \\ R_2 \\ R_3 \\ R_4 \\ R_5 \end{Bmatrix}$$

$$R_1 = \bar{\alpha}_0 - \alpha_{e_0} - \frac{2V^2}{\pi r_\alpha^2} \bar{c}_{m_0}$$

$$R_2 = \left\{ \frac{\mathrm{Re}(\bar{c}_{l_1})}{\pi \bar{\alpha}_1} - \frac{1}{4} \mu \bar{\omega}^2 \left[\frac{m_h}{m} \mathrm{Re}\left(\frac{\bar{h}_1}{\bar{\alpha}_1 b}\right) + x_\alpha \right] \right\} V^2$$
$$- \sqrt{\mu} \bar{\omega} \zeta_h \left(\frac{\omega_h}{\omega_\alpha}\right) \mathrm{Im}\left(\frac{\bar{h}_1}{\bar{\alpha}_1 b}\right) V + \left(\frac{\omega_h}{\omega_\alpha}\right)^2 \mathrm{Re}\left(\frac{\bar{h}_1}{\bar{\alpha}_1 b}\right)$$

$$R_3 = - \left\{ 2 \frac{\mathrm{Re}(\bar{c}_{m_1})}{\pi \bar{\alpha}_1} + \frac{1}{4} \mu \bar{\omega}^2 \left[x_\alpha \mathrm{Re}\left(\frac{\bar{h}_1}{\bar{\alpha}_1 b}\right) + r_\alpha^2 \right] \right\} V^2$$
$$+ r_\alpha^2$$

$$R_4 = \left[\frac{\mathrm{Im}(\bar{c}_{l_1})}{\pi \bar{\alpha}_1} - \frac{1}{4} \mu \bar{\omega}^2 \frac{m_h}{m} \mathrm{Im}\left(\frac{\bar{h}_1}{\bar{\alpha}_1 b}\right) \right] V^2$$
$$- \sqrt{\mu} \bar{\omega} \zeta_h \left(\frac{\omega_h}{\omega_\alpha}\right) \mathrm{Re}\left(\frac{\bar{h}_1}{\bar{\alpha}_1 b}\right) V + \left(\frac{\omega_h}{\omega_\alpha}\right)^2 \mathrm{Im}\left(\frac{\bar{h}_1}{\bar{\alpha}_1 b}\right)$$

$$R_5 = - \left[2 \frac{\mathrm{Im}(\bar{c}_{m_1})}{\pi \bar{\alpha}_1} + \frac{1}{4} \mu \bar{\omega}^2 x_\alpha \mathrm{Im}\left(\frac{\bar{h}_1}{\bar{\alpha}_1 b}\right) \right] V^2$$
$$+ \sqrt{\mu} \bar{\omega} V \zeta_\alpha r_\alpha^2$$

NASA BSCW Aeroelastic Configuration Transonic RANS CFD Model

Structural Parameters:
$x_\alpha = 0.0$, $r_\alpha^2 = 1.024$, $(\omega_h/\omega_\alpha) = 0.646$,
$\zeta_h = 0.002$, $\zeta_\alpha = 0.002$,
$a = 0.0$, and $\alpha_{e_0} = 5.0^\circ$.

Computational Grid - 193×49 "O-Mesh":

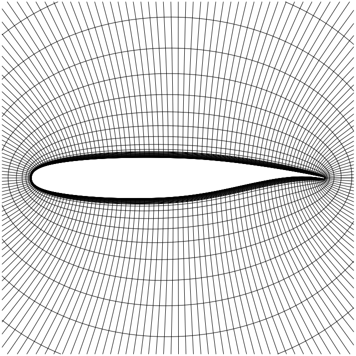


Figure: Computational Grid.

NASA BSCW Aeroelastic Configuration Transonic RANS CFD Model Continued

Flow Near the Flutter-Onset Condition:
$M_\infty = 0.80$, $Re_\infty \approx 4,000,000$, $\bar{\alpha}_0 \approx 6.15^\circ$, and $\mu \approx 1100$.

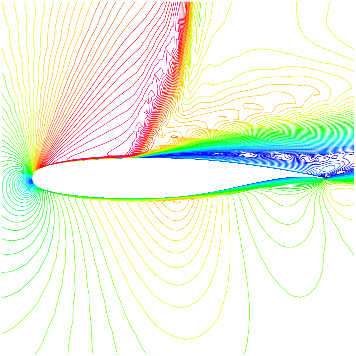


Figure: Mean Flow Mach Number Contours.

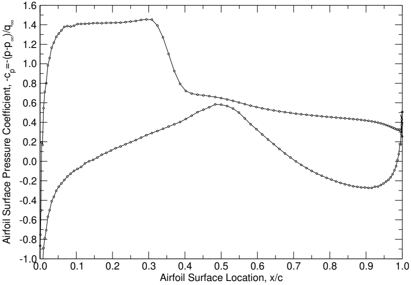
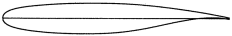


Figure: Mean Surface Pressure Coefficient.

Airfoil Geometric Shape Definition / Might "Better" Tabulated Data Be Available?

Tabulated data is only given to at most three significant figures.

Table XIX. Coordinates of 14-Percent-Thick Supercritical Airfoil SC(2)-0414
Designed for 0.4 Lift Coefficient



x/c	$(y/c)_u$	$(y/c)_l$	x/c	$(y/c)_u$	$(y/c)_l$
0.000	0.0000	0.0000	.500	.0684	-.0642
.002	.0108	-.0108	.510	.0680	-.0633
.005	.0166	-.0166	.520	.0676	-.0623
.010	.0225	-.0225	.530	.0672	-.0612
.020	.0299	-.0299	.540	.0667	-.0600
.030	.0350	-.0350	.550	.0662	-.0587
.040	.0389	-.0389	.560	.0656	-.0573
.050	.0421	-.0421	.570	.0650	-.0558
.060	.0448	-.0448	.580	.0643	-.0543
.070	.0471	-.0472	.590	.0636	-.0527
.080	.0491	-.0493	.600	.0628	-.0510
.090	.0510	-.0512	.610	.0620	-.0492
.100	.0527	-.0529	.620	.0611	-.0474
.110	.0542	-.0545	.630	.0602	-.0455
.120	.0556	-.0560	.640	.0593	-.0435
.130	.0569	-.0573	.650	.0583	-.0415
.140	.0581	-.0585	.660	.0573	-.0394
.150	.0592	-.0597	.670	.0562	-.0373
.160	.0602	-.0608	.680	.0551	-.0352
.170	.0612	-.0618	.690	.0540	-.0330
.180	.0621	-.0627	.700	.0528	-.0308
.190	.0629	-.0636	.710	.0516	-.0286
.200	.0637	-.0644	.720	.0503	-.0264
.210	.0644	-.0651	.730	.0490	-.0242
.220	.0651	-.0658	.740	.0477	-.0220
.230	.0657	-.0664	.750	.0464	-.0198
.240	.0663	-.0670	.760	.0450	-.0177
.250	.0668	-.0675	.770	.0436	-.0156
.260	.0673	-.0680	.780	.0422	-.0136
.270	.0677	-.0684	.790	.0407	-.0116
.280	.0681	-.0688	.800	.0392	-.0097
.290	.0685	-.0691	.810	.0377	-.0078
.300	.0688	-.0694	.820	.0362	-.0060
.310	.0691	-.0696	.830	.0346	-.0043
.320	.0693	-.0698	.840	.0330	-.0027
.330	.0695	-.0699	.850	.0314	-.0012
.340	.0697	-.0700	.860	.0298	.0001
.350	.0699	-.0700	.870	.0281	.0013
.360	.0700	-.0700	.880	.0264	.0023
.370	.0701	-.0699	.890	.0247	.0032
.380	.0702	-.0698	.900	.0229	.0039
.390	.0702	-.0697	.910	.0211	.0044
.400	.0702	-.0695	.920	.0193	.0046
.410	.0702	-.0693	.930	.0175	.0046
.420	.0701	-.0690	.940	.0156	.0043
.430	.0700	-.0686	.950	.0137	.0038
.440	.0699	-.0682	.960	.0117	.0031
.450	.0697	-.0677	.970	.0097	.0021
.460	.0695	-.0672	.980	.0076	.0008
.470	.0693	-.0666	.990	.0055	-.0008
.480	.0690	-.0659	1.000	.0033	-.0027
.490	.0687	-.0651			

Figure: Airfoil Definition from Harris[1]

[1] Charles D. Harris. *NASA Supercritical Airfoils - A Matrix of Family Related Airfoils*. NASA Technical Paper 2969. Mar. 1990.

NASA BSCW Aeroelastic Configuration Improved Airfoil Definition

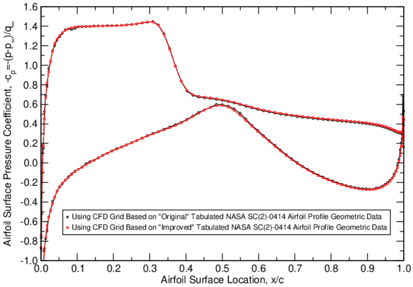


Figure: Airfoil Surface Pressure.

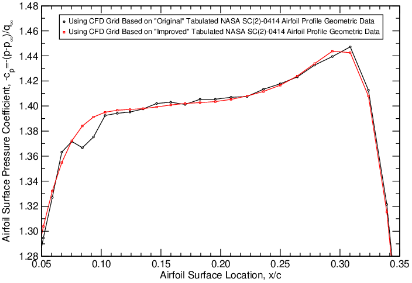
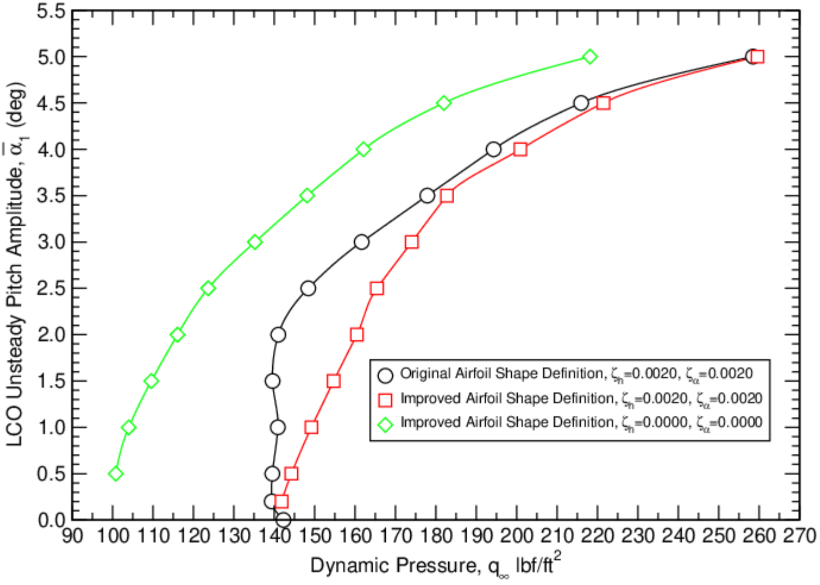
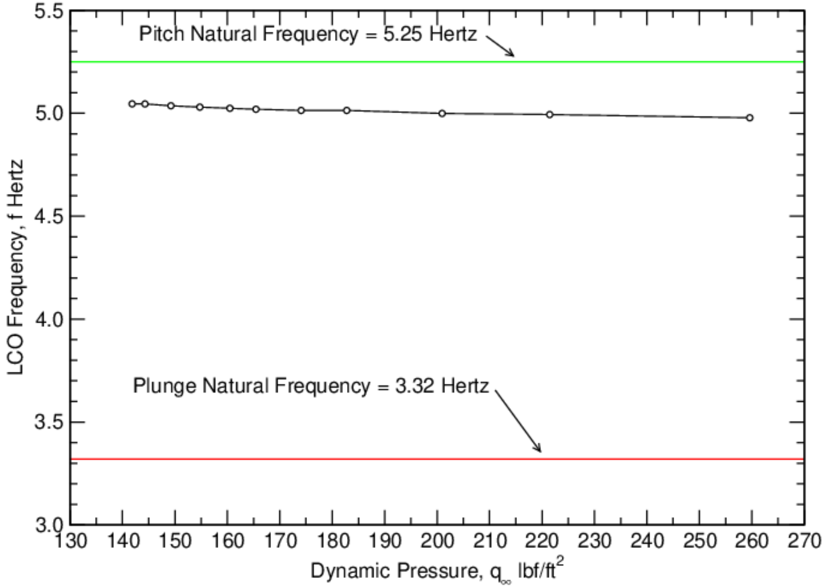


Figure: Airfoil Surface Pressure - Close-up.

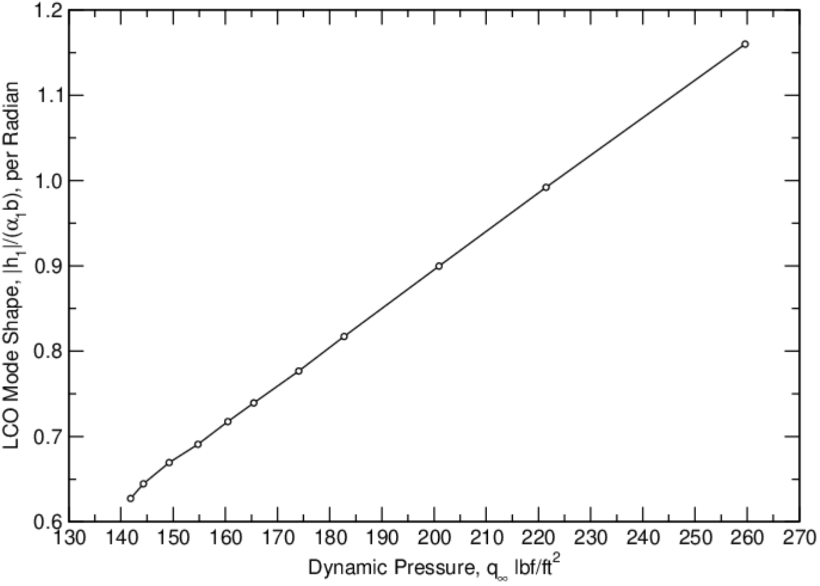
NASA BSCW Aeroelastic Configuration Computed LCO Unsteady Pitch Response Trend



NASA BSCW Aeroelastic Configuration Computed LCO Frequency Response Trend



NASA BSCW Configuration Computed LCO Aeroelastic Mode Shape Response Trend



NASA BSCW Configuration Computed LCO Mean Angle-of-Attach Response Trend

Original Airfoil Surface Definition