2D Simulation of Transonic Buffet Using Direct Solutions to Navier-Stokes

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Transonic buffet is a dynamic fluid instability which, for sufficiently high Mach numbers and angles of attack, produces a limit cycle oscillation in the coefficient of lift. This limit cycle generates dynamic loads on the aircraft which constrain the flight envelope. The goal of this independent study is to better understand the flow conditions and modeling parameters which lead to buffet onset using computational fluid dynamics (CFD). In particular, this paper aims to capture sustained buffet in the transonic range by directly solving the Navier-Stokes equations without a turbulence model.

Nomenclature

M	=	free-stream Mach number
α	=	angle of attack (degrees)
Re	=	chord-based Reynolds number
t	=	flow time (s)
Δt	=	time step (s)
C_L	=	lift coefficient
ΔC_L	=	peak to peak lift coefficient
$\overline{C}_L$	=	mean lift coefficient
c	=	chord (m)

I. Introduction

For high subsonic Mach numbers, increasing the angle of attack beyond a certain threshold is known to induce large-scale limit cycle oscillations in the shock position and coefficient of lift. This fluid instability, accompanied by downstream flow separation, is known as transonic buffet. The buffet limit cycle is self-sustaining and creates dynamic loads on the aircraft wing. The resulting vibrations can weaken the structure of the aircraft and lead to failure by fatigue, thereby constraining the flight envelope. It is important in designing modern aircraft, then, to understand the conditions which give rise to buffeting flow in order to minimize shock wave oscillations and delay the onset of buffet.

Buffet has been studied both experimentally and computationally over the last few decades. Attempts to capture buffet numerically in two dimensions have achieved reasonable agreement with experimental results using the unsteady Reynolds-averaged Navier-Stokes method (URANS). This approach is particularly sensitive to the selection of turbulence model, however, with one of the most prevalent choice being the Spalart-Allmaras formulation [1]. While URANS simulations have proven successful in modeling the large-scale pattern of transonic buffet, namely in capturing the frequency of shock oscillations, they fail to resolve the smaller scale turbulent structures of buffeting flow. For this reason, growing research attention has been devoted to scale-resolving simulation methods like Large Eddy Simulation (LES), hybrid RANS/LES, and Detached Eddy Simulation (DES) [2–4]. These methods are more computationally demanding than URANS, but are able resolve a much wider spectrum of turbulence in numerical buffet simulations.

The goal of the present study is to capture the onset and sustained behavior of transonic buffet in two dimensions by directly solving the Navier-Stokes equations without a turbulence model. This approach to simulating buffet is used to resolve the smaller turbulent scales for comparison with both experimental trends and previous results obtained with URANS methods.

II. Description of Numerical Method

A. Flow Conditions

The simulations in this paper deal with flow over a NACA 0012 symmetric airfoil at a Mach number of 0.76 and a Reynolds number $Re = 10 \times 10^6$. The considered range of attack angles is $2.5° \leq \alpha \leq 12°$. Stability results from McDevitt & Okuno [5] and Crouch et al. [6] for the NACA 0012 airfoil at a Reynolds number $Re = 10 \times 10^6$ are given in Figure 1. The buffet onset boundary for a Mach number 0.76 is at an angle of attack $\alpha \approx 3°$.

B. Computational Model

All studies included in this paper are performed in ANSYS Fluent 19.2 using a coupled pressure-based solver with a Courant number of 5. All nonzero angles of attack are set over 5 time steps beginning at $t = 0.4$s by linearly rotating the mesh by the desired angle α. The flow time $t = 0.4$s was chosen to provide sufficient time for the solution at zero angle of attack to settle. Unless otherwise specified, solutions are obtained using the Second Order spatial discretization scheme for pressure and the Third-Order MUSCL discretization scheme for density, momentum, and energy. The computational grid used was generated by Bastos et al. [7] using GMSH and features a structured near-field with 640 points on the airfoil. A close-up view of this grid is shown in Figure 2.

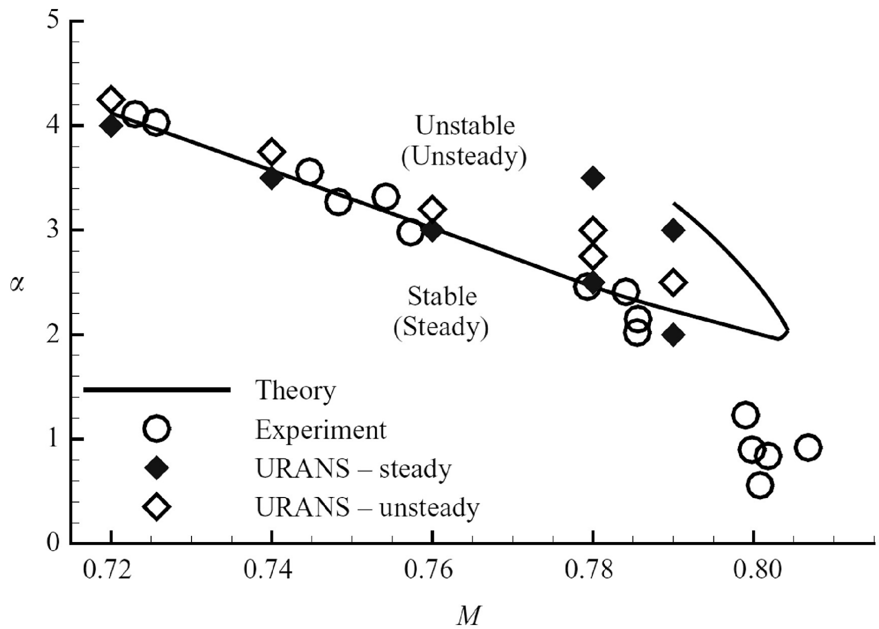


Fig. 1 Buffet onset boundary for NACA 0012 airfoil at $Re = 10 \times 10^6$ from McDevitt & Okuno [5] and Crouch et al. [6]

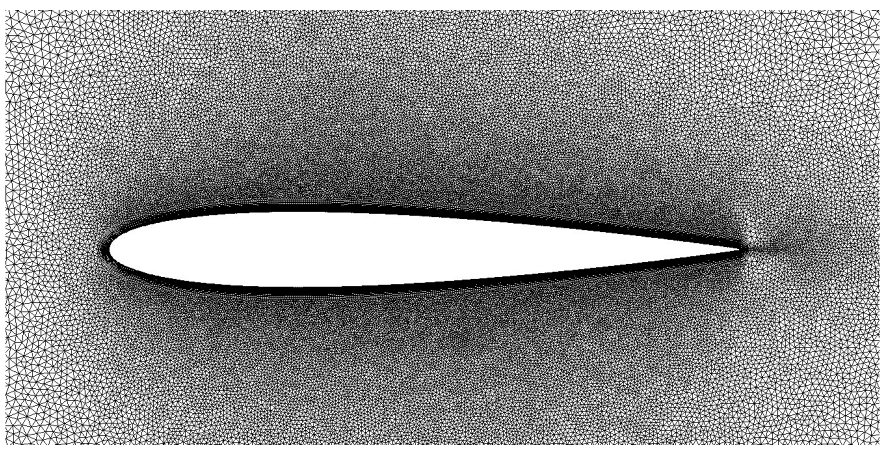


Fig. 2 Close-up view of computational grid from Bastos et al. [7]

III. Simulation Results and Process

A. Model Verification with URANS

Before beginning any studies using direct solutions to the Navier-Stokes equations, a series of URANS experiments were performed to verify that this computational model produces reasonable results. The first such experiment takes a known case of buffet for the NACA 0012 airfoil at $\alpha = 6°$, Mach 0.72, and a Reynolds number $Re = 10 \times 10^6$. The results of this simulation, shown in Figure 3, show clear self-sustained buffet, as expected.

Additional URANS simulations were then performed at a Mach number of 0.76, which is the flow condition of particular interest in this paper. These simulations did not establish clear buffet, but produced reasonable results, which give confidence to the computational model. A plot of the transient lift coefficient for Mach 0.76 and $\alpha = 4°$ is shown in Figure 4.

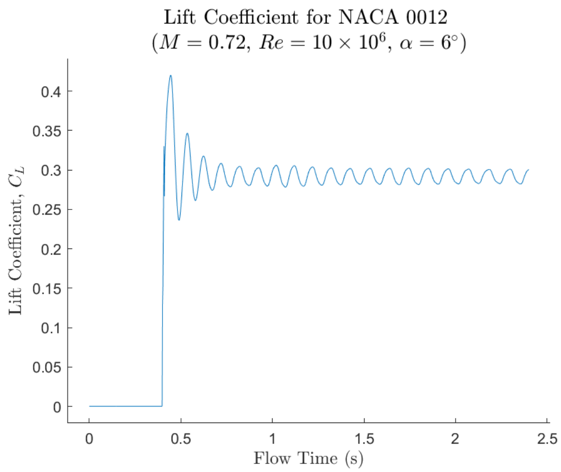


Fig. 3 Self-sustained buffet obtained with URANS at $M = 0.72$, $Re = 10 \times 10^6$, and $\alpha = 6°$

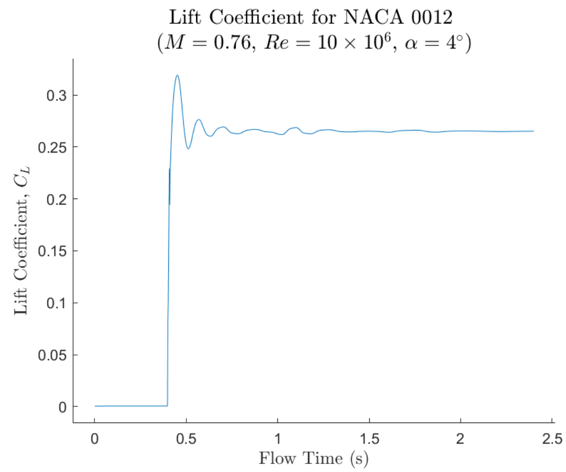


Fig. 4 Lift coefficient results obtained with URANS at $M = 0.76$, $Re = 10 \times 10^6$, and $\alpha = 4°$

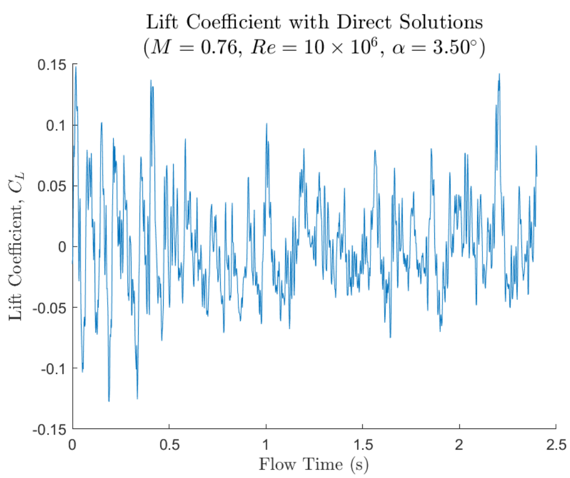


Fig. 5 Transient lift coefficient results obtained with direct solutions at $\alpha = 3.50°$

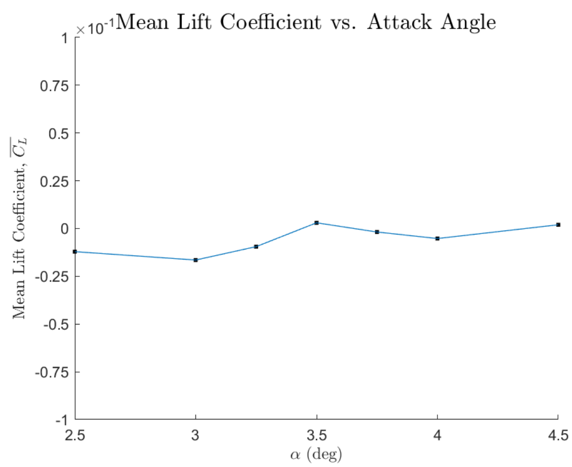


Fig. 6 Mean lift coefficient by attack angle, obtained using direct solutions

B. Implementing Simulation with Direct Solutions

Early attempts to capture buffet with direct solutions to Navier-Stokes revealed very erratic patterns in the lift coefficient with notably small magnitudes. The lift coefficient output for one of these runs at $\alpha = 3.50°$ is shown in Figure 5. As depicted in Figure 6, the mean lift coefficients for all angles of attack $2.50° \leq \alpha \leq 4.50°$ are approximately zero. Additionally, since there is no obvious change in lift at $t = 0.4$s, it is not clear whether the airfoil rotated properly. The next round of simulations is designed primarily to troubleshoot these low magnitude lift coefficient results.

Another useful method for analyzing these results is to plot the non-dimensional amplitude and frequency of the

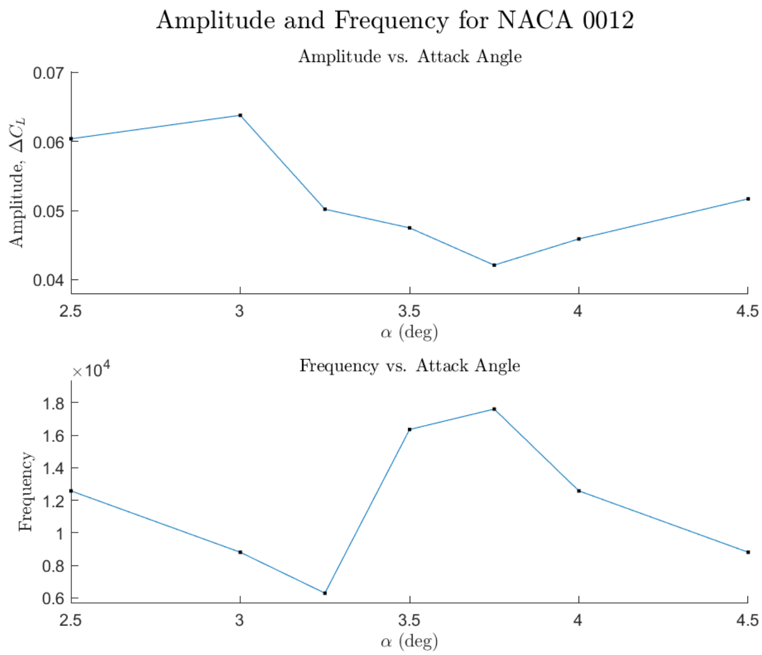


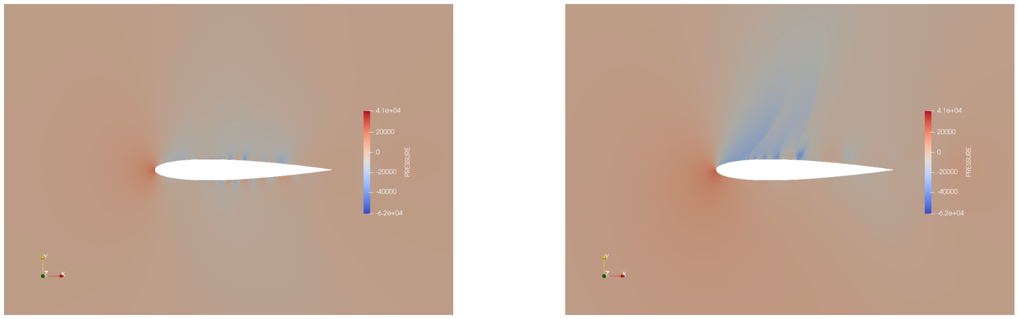
Fig. 7 Non-dimensional amplitude and frequency plots using direct solutions to Navier-Stokes

transient lift coefficient for each angle of attack. At the onset of buffet, both the amplitude and frequency are expected to quickly rise to their peak values. As the angle of attack is further increased, amplitude tends to decrease slowly while frequency stays relatively constant until buffeting stops and the amplitude settles back to zero. Recall that, based on the results in Figure 1 from McDevitt & Okuno [5] and Crouch et al. [6], we expect this flow to begin buffeting around $\alpha \approx 3°$. In the amplitude and frequency plots generated from these direct solution runs (Figure 7), a peak in the frequency can be observed between 3.50° and 4.00°, but there is no corresponding peak in the plot of amplitude. It is important to note that, while the frequency plot may behave reasonably from a qualitative standpoint, its magnitude is far higher than expected.

C. Verification of Airfoil Rotation

In light of the near-zero lift coefficient obtained in previous simulations, it became of interest to verify proper rotation of the airfoil at $t = 0.4$s. Two methods were employed in this process. First, a visual representation of a simulation at $\alpha = 10°$ was generated in the form of a GIF. Two snapshots from this GIF, one at $t = 0.39$s and one at $t = 0.40$s, are shown in Figure 8. From these images it is clear that there is a change in attack angle at the expected flow time.

The second method of verifying proper rotation of the airfoil was to run a series of simulations at higher angles of attack. At these larger angles, the lift does increase visibly following the rotation of the airfoil. One such lift coefficient plot at $\alpha = 12°$ is shown below in Figure 9. This plot is also notably less erratic than those at lower angles of attack; though the magnitude of the mean lift coefficient is still significantly below the expected value.



(a) At t = 0.39**s** **(b) At** t = 0.40**s**

Fig. 8 GIF snapshots before and after the airfoil rotation

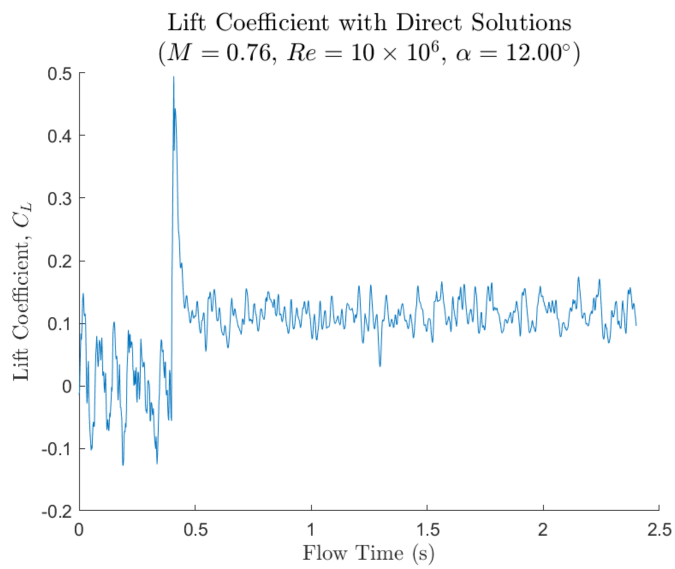


Fig. 9 Lift coefficient results obtained with direct solutions at $\alpha = 12.00^\circ$

D. Residual Tuning

The next approach taken to diagnose issues with the simulations and to produce more reasonable results was an analysis of the residuals. Simulations at multiple angles of attack were performed with varying continuity residuals. The values tested for the continuity residual threshold ranged from 2.5×10^{-5} to 10^{-2}. In all of these simulations, the residual thresholds for x-velocity, y-velocity, and energy are set to 10^{-6}. Plots of the residual values at each sub-iteration for a simulation at $\alpha = 12^\circ$ and a continuity residual threshold of 10^{-2} are given below in Figure 10. From these residual plots, it is clear that even the least stringent criteria for the continuity residual fails to be satisfied. Naturally, then, the residual plots obtained from simulations with lower continuity residual thresholds are identical to those shown in Figure 10. It is important to note that the residual values are reasonably settled at the end of 100 sub-iterations, so increasing the number of sub-iterations would be unlikely to cause any improvements.

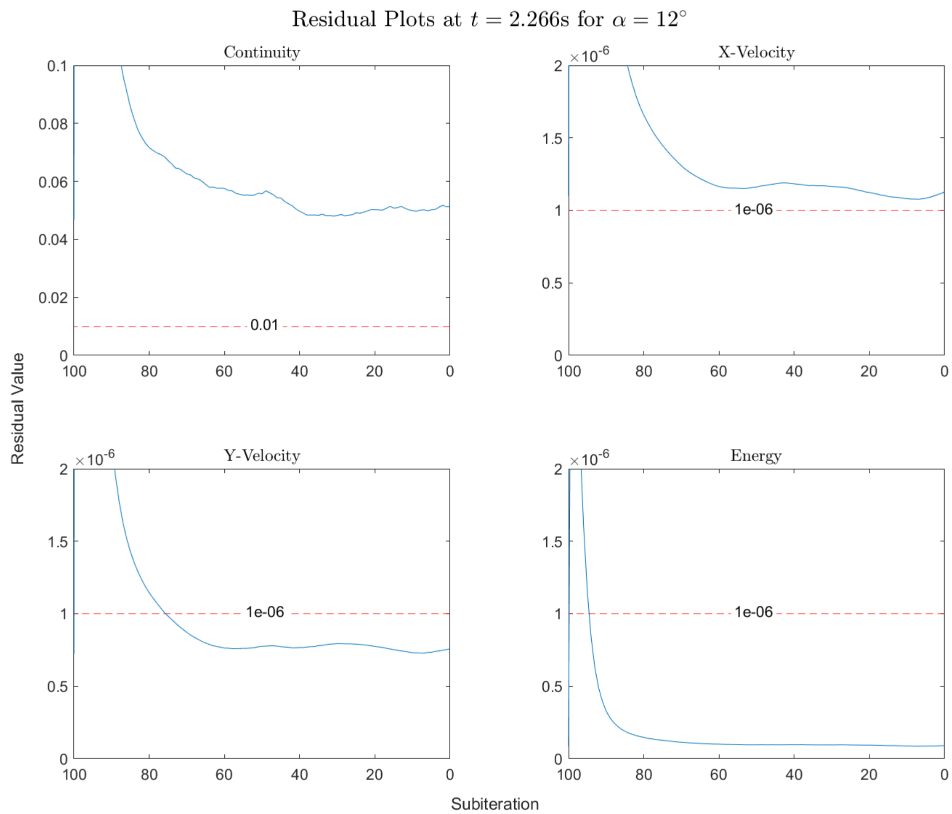


Fig. 10 Residual plots with direct solutions at $\alpha = 12.00^\circ$

E. Reduced Time Step

To promote faster convergence at each time step and reduce the overall residuals, a series of simulations were performed with reduced time steps. The previous simulations used a time step $\Delta t = 0.002$s, which is large compared to the recommended time step based on the ANSYS Fluent manual. From Bastos et al. it is given that the grid density on the airfoil surface is 0.312% of the chord [7]. Given the chord $c = 1$m, free stream Mach number $M = 0.76$, and the speed of sound at altitude $c_s = 316.431$m/s, a conservative estimate for the appropriate time step Δt can be computed as follows:

$$\Delta t \approx \frac{\text{Minimum cell size}}{\text{Characteristic flow velocity}} = \frac{0.00312 \text{ m}}{0.76 \cdot 316.431 \text{ m/s}} = 1.29 \times 10^{-5} \text{ s} \tag{1}$$

At a time step of $\Delta t = 0.001$s, the residual plots show significant improvement and the mean lift coefficients increase notably. An analogous residual plot to Figure 10 with a 50% reduced time step is shown below in Figure 11. Note that the x-velocity residual now meets the convergence criteria and the continuity residual, while still failing to satisfy the criteria, is substantially lower after 100 sub iterations. The lift coefficient results for $\alpha = 12^\circ$, as shown in Figure 12, are also promising. Compared with the mean lift coefficient $\overline{C}_L \approx 0.1142$ in Figure 9, the value obtained with a reduced time step is about 388% higher at $\overline{C}_L \approx 0.4428$. These results along with the estimation given in Equation 1 motivate further reductions in the time step.

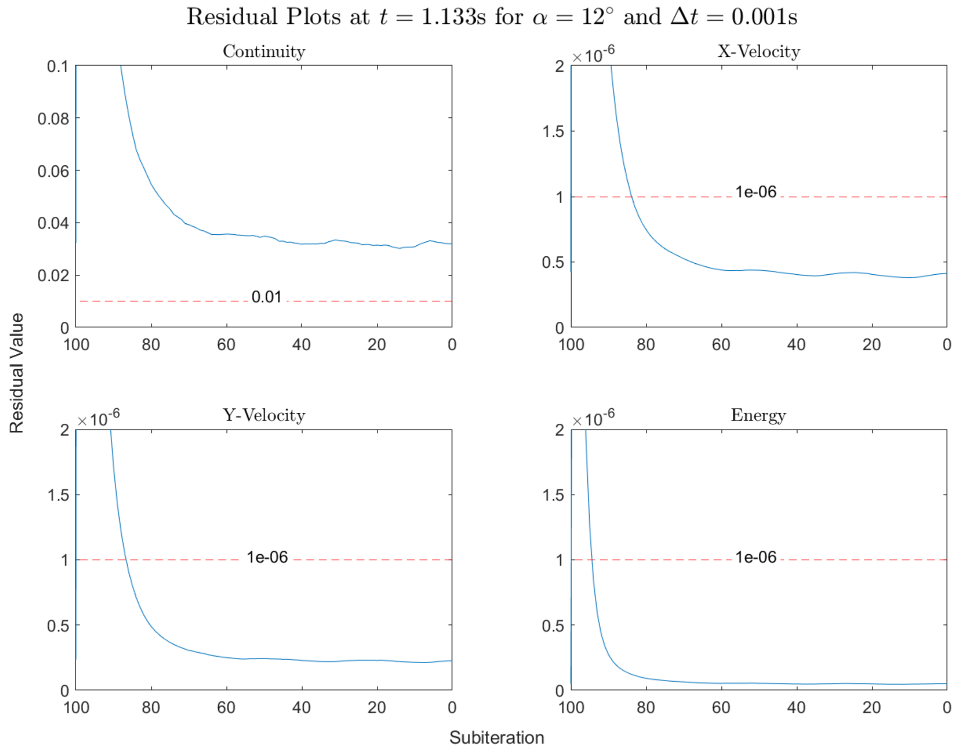


Fig. 11 Residual plots with direct solutions at $\alpha = 12.00°$ and a reduced time step $\Delta t = 0.001$s

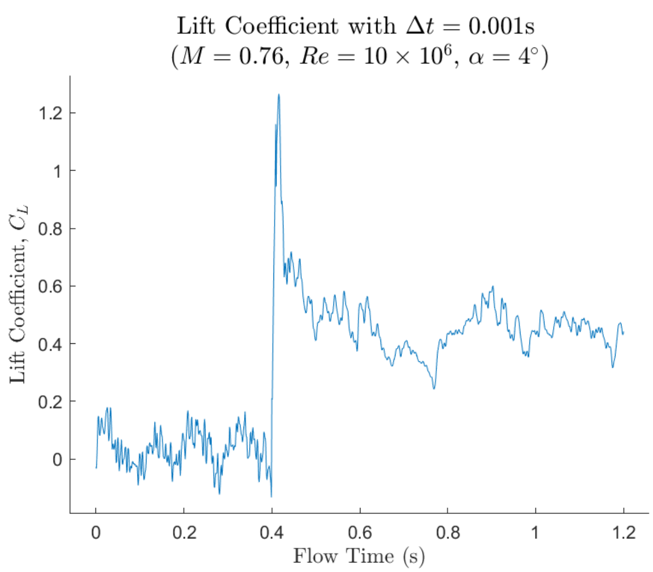


Fig. 12 Lift coefficient results obtained with direct solutions at $\alpha = 12.00°$ and a reduced time step $\Delta t = 0.001$s

IV. Concluding Remarks

Ultimately, sustained buffet was not successfully captured in this study using direct solutions to Navier-Stokes; however, the results presented in this paper do show some promise for future experiments. The immediate next steps in this research will be aimed at deriving the optimal time step for simulation to produce reasonable results within a reasonable amount of time. A plausible procedure for this goal would be to iteratively reduce the time step until either the results cease to differ significantly between runs or until the time required to complete the simulation exceeds reasonable bounds. At this point, relaxation factors can be explored as a means to further improve convergence behavior, if necessary. Once residual convergence is achieved and the lift coefficients fall within a sensible range, it will be interesting to revisit the amplitude and frequency plots to study the flow behavior near or at the point of expected buffet onset. These results could then be compared to analogous work obtained with URANS to provide insight into the simulation behavior and mechanisms of transonic buffet.

As an independent study, this project provided a great learning experience for me, as I gained my first in-depth exposure to both transonic buffet and CFD as a research tool. I thoroughly enjoyed the process of learning from the existing body of research and developing a working understanding of transonic buffet. It was also fascinating to explore the physical dynamics and approximations which govern CFD simulations and how they can be affected by parameter tuning. Finally, my consistent use of the Duke Compute Cluster (DCC) for running expensive simulations encouraged me to develop more efficient ways to manage finite computing resources. Since each simulation on the cluster takes several days to run, over the course of the semester I learned how to better design experiments and schedule jobs in order to increase my productivity.

Acknowledgments

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