Control of Leading Edge Vortex and Three-Dimensional Surface Separation on a Non-Slender Delta Wing Using Passive and Active Techniques

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Motivation and Objective:

In recent decades, there has been a significant increase in studies focusing on the characterization of flow structures over delta wings with a sweep angle Λ of less than 55 degrees. These planforms provide valuable data for the advanced design of Unmanned Aerial Vehicles (UAVs), Unmanned Combat Aerial Vehicles (UCAVs), and Micro Aerial Vehicles (MAVs). It is also anticipated that in the near future, such delta wing geometries will serve as baseline models for manned aircraft, given their growing popularity in recent years.

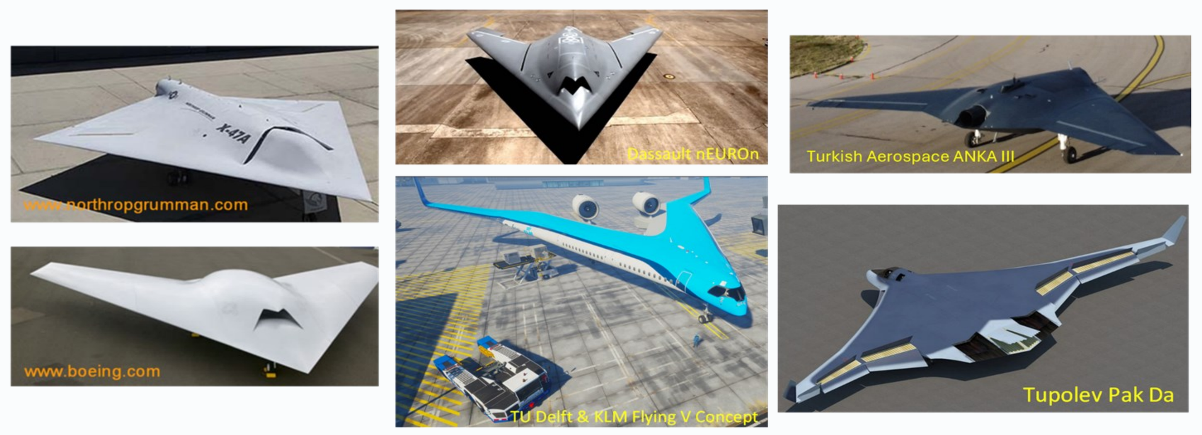

Figure 1 Sample manned and unmanned air vehicles representing delta planform models.

Recent studies have shown that, among various passive and active flow control approaches, passive bleeding and periodic blowing can effectively control flow structures on non-slender delta wings. These methods particularly focus on eliminating three-dimensional surface separation, enhancing the leading edge vortex, and delaying stall. However, there are still very few studies investigating the comprehensive impact of passive bleeding techniques on vortex-dominated aerodynamic surfaces. Innovative bleeding geometries could enhance effectiveness in terms of aerodynamic performance and stability. Despite the increased popularity of periodic excitation techniques on non-slender delta wings, their impacts need further investigation, particularly concerning multi-control parameter sensitivity and the assessment of aerodynamic loads and stability.

The aim of the present study is to control the complex flow structures over a delta wing with a sweep angle Λ of 45 degrees using passive and active techniques, specifically passive bleeding and periodic blowing. For the passive technique, the study investigated the effect of a novel bleeding geometry design with a nozzle cross-section aimed at increasing the bleeding momentum. Additionally, a method for estimating the passive bleeding momentum coefficient was developed. For the periodic blowing technique, the effect of square wave type actuation applied through the leading edges was studied. Two main configurations were tested: regular signal and burst modulated signal, using an in-house active blowing flow control system. A detailed matrix was developed to assess the sensitivity of the active flow control parameters. Prior to aerodynamic measurements, a comprehensive characterization of the flow control system was conducted using in-situ approaches to test and construct calibration charts for each control parameter.

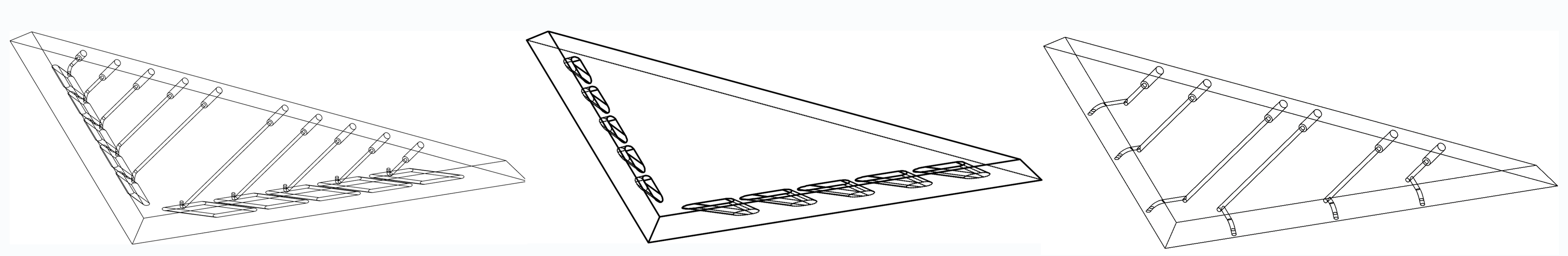

Figure 2 Isometric views of the tested wing models.

Methodology:

This experimental work was conducted in a low-speed wind tunnel facility at the Fluid Mechanics Laboratory of the Mechanical Engineering Department at Middle East Technical University. The experiments were performed at $3.5\times10^4 \le Re \le 1\times10^5$ and $0^\circ \le \alpha \le 30^\circ$, using the techniques of surface pressure, force balance, hot wire anemometry, and near-surface particle image velocimetry measurements.

For the passive technique, four different nozzle wing models were tested in comparison to a baseline delta wing model for the defined nozzle bleed geometry parameter namely a contraction ratio of CR = 1:0.5 and CR = 1:0.75. Bleed momentum calibration experiments were performed in two stages, namely Stage 1 and Stage 2.

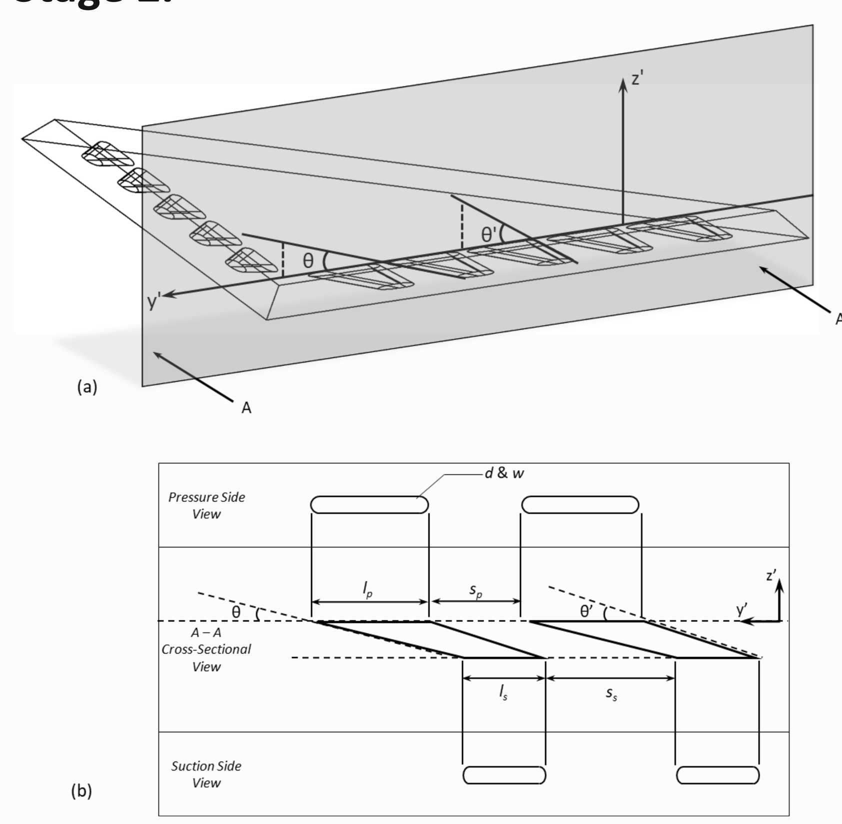

Figure 3 Schematic of the nozzle bleeding wing design.

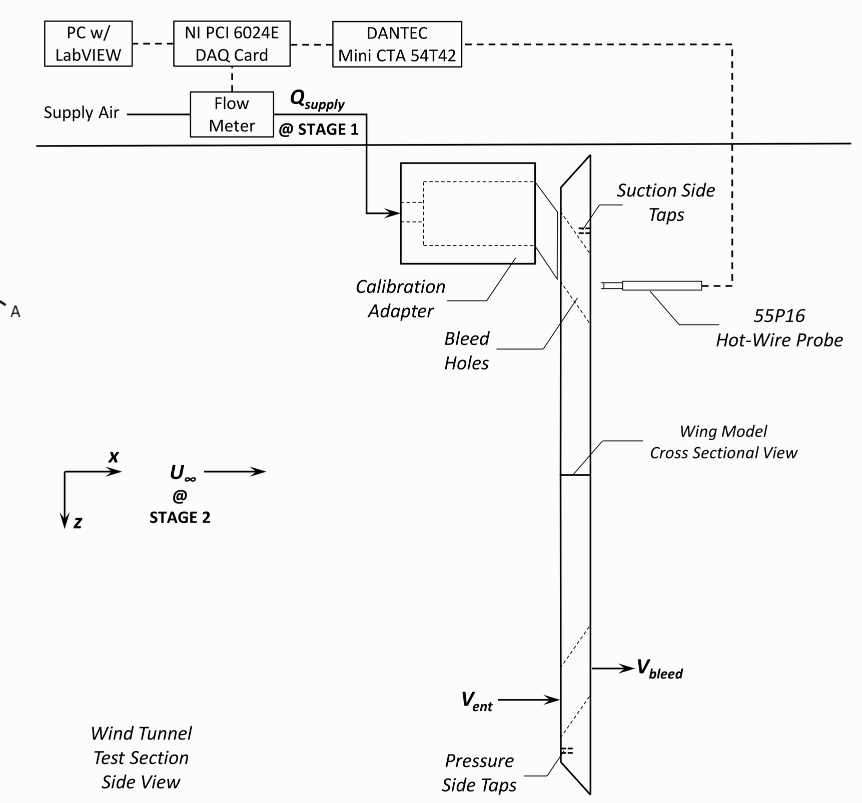

Figure 4 Schematic representation bleed momentum estimation approach.

During active flow control campaign, for the regular square wave periodic blowing actuation, an excitation frequency range of $1 \le f_c \le 64$ Hz was tested for two different duty cycle settings of DC_c = 25% and 50%, at a maximum momentum coefficient value of $C_{\mu,max}$ = 1%. For the burst modulated square wave cases, experiments were performed for a carrier frequency range of $4 \le f_c \le 64$ Hz with carrier duty cycle settings of DC_c = 25% and 50% and a modulating frequency range of $1 \le f_m \le 4$ Hz Hz with modulating duty cycle settings of DC_m = 50%.

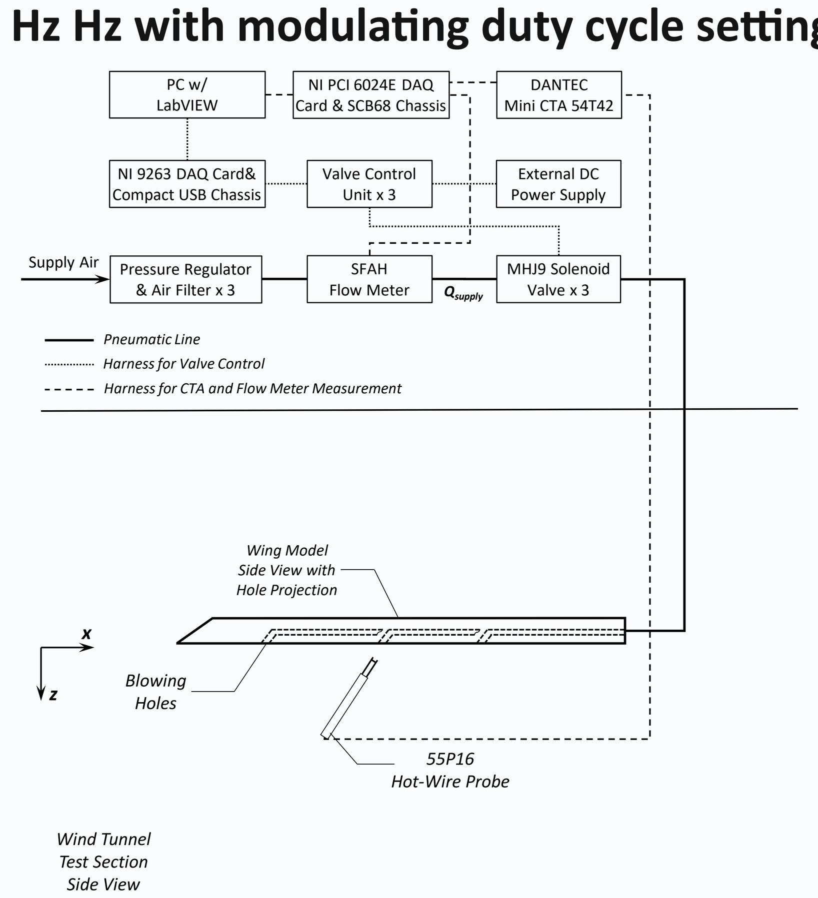

Figure 5 Schematic representation active flow control system.

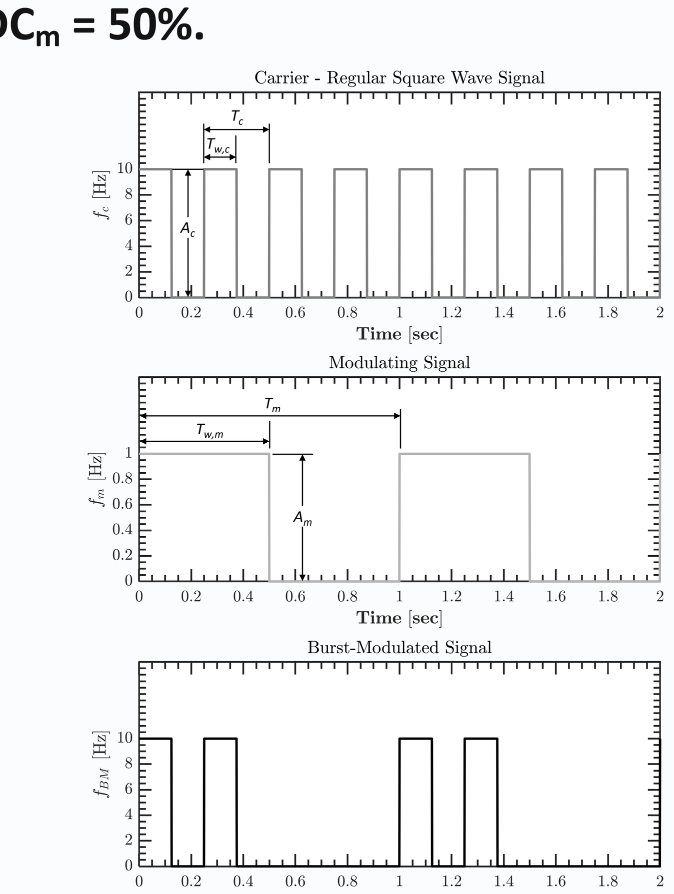

Figure 6 Square wave signal designations: Regular, modulating and burst modulated square wave.

Results:

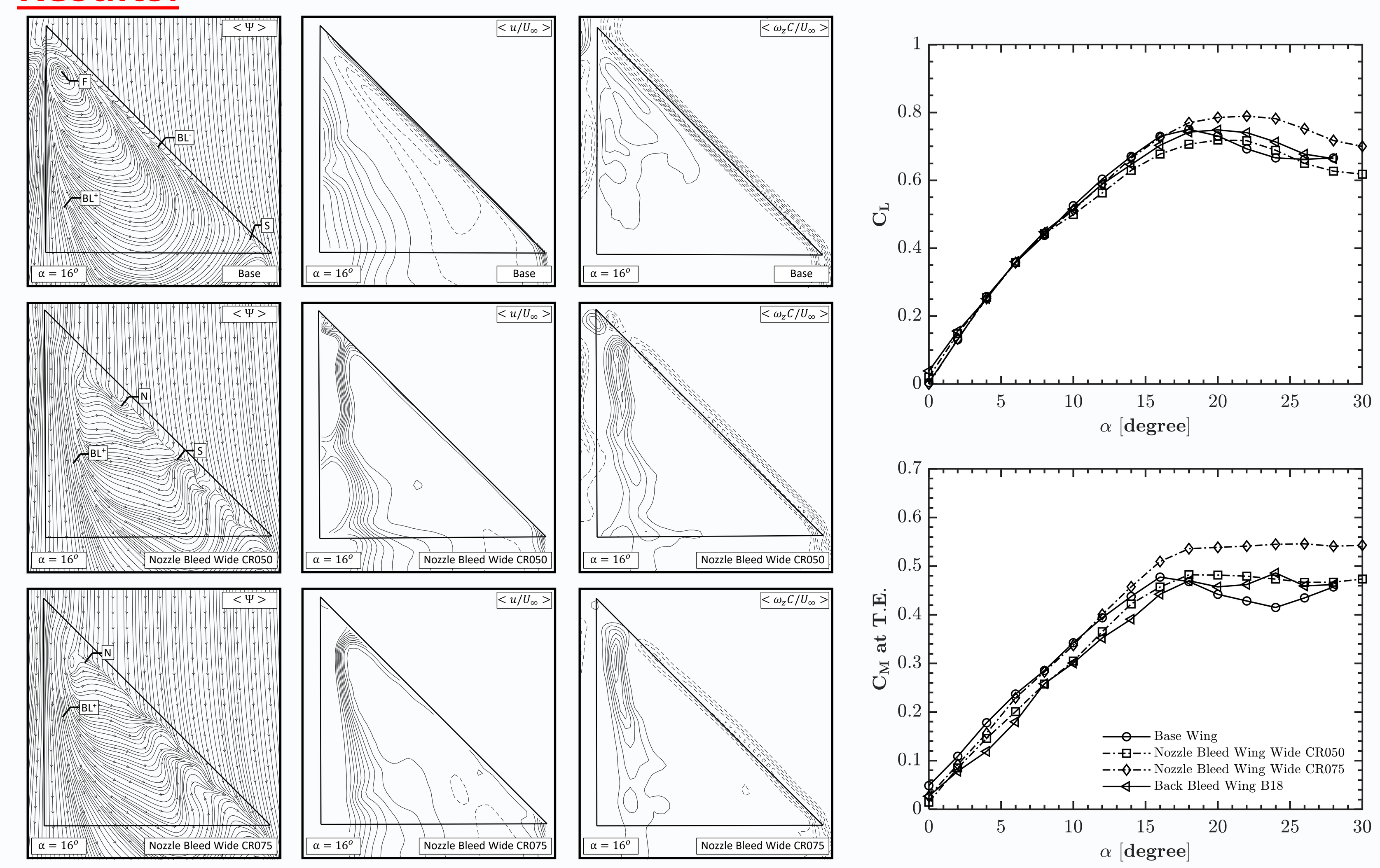

Figure 7 Nozzle bleeding wing design results : PIV measurements, $\alpha = 16^o$ - $Re = 3.5x10^4$ and Force measurements, $0^o \le \alpha \le 30^o$- $Re = 9x10^4$

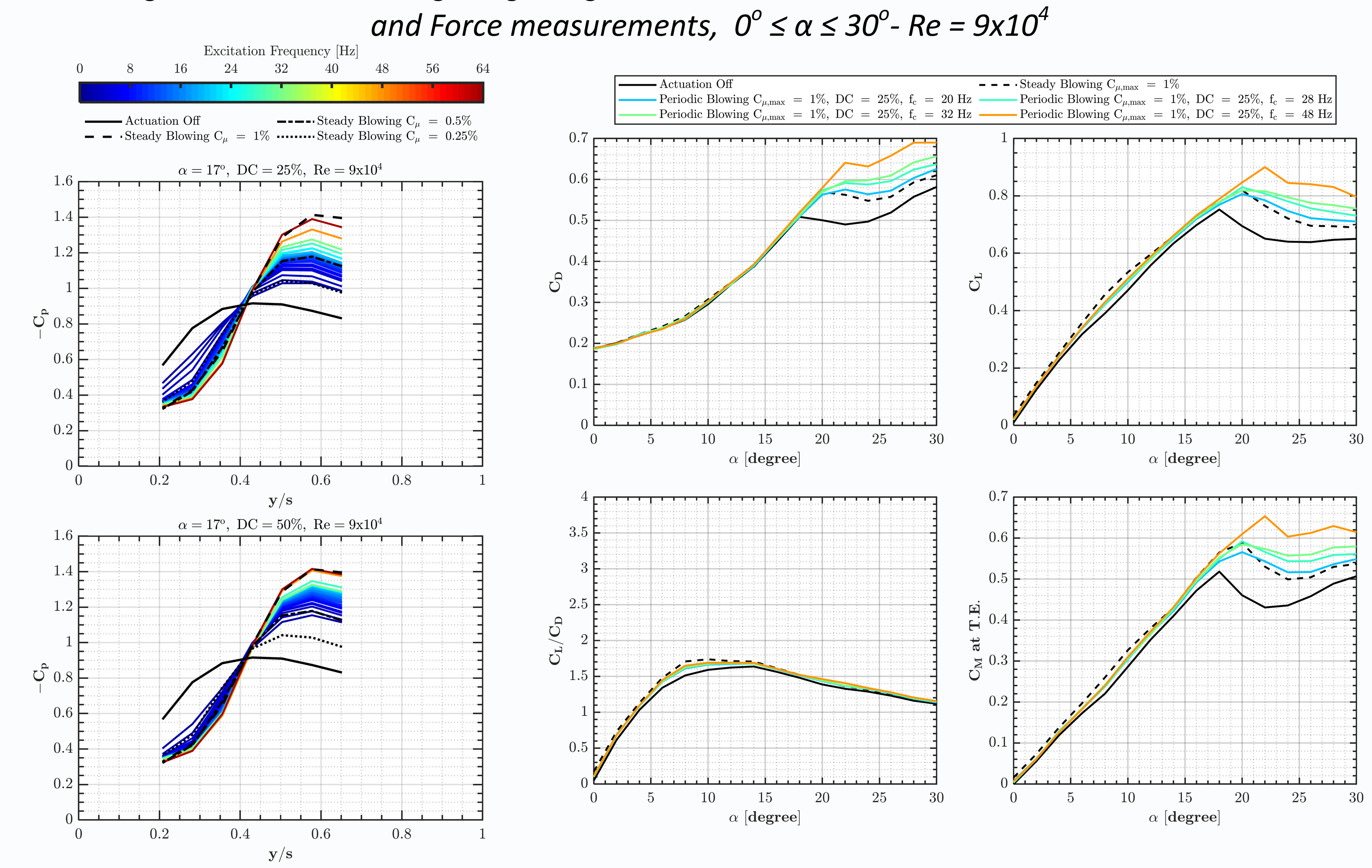

Figure 8 Regular square wave blowing results: Surface pressure measurements, $\alpha = 16^o$ - $Re = 9x10^4$ and Force measurements, $0^o \le \alpha \le 30^o$- $Re = 9x10^4$.

Conclusions:

1) Bleed momentum estimation suggests surface pressure taps near bleeding slot inlets and outlets on a nonslender delta wing can estimate across-slot momentum coefficients with controlled calibration.
2) Nozzle bleeding slots modify the surface flow field by preventing or altering three-dimensional separation, enhancing lift and stability despite increased drag. This technique shows promise for active bleeding system design.
3) Investigations highlight the value of characterizing an in-house active flow control system using fast-switching pneumatic valves to assess blowing sensitivity to control parameters like frequency, duty cycle, and momentum coefficient. Blowing hole geometry and pipeline layout are critical.
4) Periodic blowing excitation is found effective in manipulating aerodynamic behavior and cross-flow surface pressure distributions, resulting in substantial improvements in lift and stability characteristics and significant recoveries in the flow field.