

High Reynolds Number Testing of the NATO AVT-298 SWiFT Configuration at the National Transonic Facility

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A high Reynolds number wind tunnel test of the NATO AVT-298 Swept Wing Flow Test (SWiFT) configuration was conducted in the National Transonic Facility at the NASA Langley Research Center during the summer of 2023. The SWiFT research model geometry has relevance to both blended/hybrid wing body (BWB/HWB) and unmanned combat aerial vehicle (UCAV) configurations, and the test campaign was the culmination of an international collaboration under the NATO AVT-298 research task group. The main objectives of the test were to investigate Reynolds number scaling effects on low-speed stability & control characteristics and to examine the onset and progression of flow separation on the wings particularly near the wing crank. Force & moment and surface pressure data were acquired at Mach numbers from 0.2 to 0.8, Reynolds numbers from 2.5 to 34 million, angles of attack from -3 to 20 degrees, and sideslip angles from -10 to 10 degrees. Boundary layer transition detection techniques utilizing static pressure taps, unsteady pressure transducers, and sublimating chemicals were used on the model in a free/natural transition state or a forced transition state using trip dots. Pressure sensitive paint was used to obtain a global surface pressure profile on the model and an advanced laser velocimetry technique was used to obtain velocity measurements in the wake downstream of the wing crank. The results from the test showed clear Reynolds number scaling effects on the maximum lift coefficient and pitching moment coefficient at Mach 0.2, while also capturing significant hysteresis effects. The data acquired from the test will ultimately help improve computational aerodynamic analysis and design tools for application to future BWB-type vehicle configurations.

Nomenclature

AFRL	Air Force Research Laboratory (USA)	Dstl	Defence Science and Technology Laboratory (United Kingdom)
AOA	Angle of Attack	ESP	Electronically Scanned Pressure
AVT	Applied Vehicle Technology	F&M	Force & Moment
BL	Boundary Layer	FLEET	Femtosecond Laser Electronic Excitation Tagging
BMC	Balance Moment Center	HWB	Hybrid Wing Body
BWB	Blended Wing Body	IGV	Inlet Guide Vanes
CAD	Computer-Aided Design	LaRC	Langley Research Center
CFD	Computational Fluid Dynamics		
DAS	Data Acquisition System		

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LE	Leading Edge	C_A	Axial force coefficient
LN ₂	Liquid Nitrogen	C_D	Drag coefficient
MRP	Moment Reference Point	C_L	Lift coefficient
N ₂	Nitrogen	C_l	Rolling moment coefficient
NASA	National Aeronautics and Space Administration	C_m	Pitching moment coefficient
NATO	North Atlantic Treaty Organization	C_N	Normal force coefficient
NTF	National Transonic Facility	C_n	Yawing moment coefficient
PSP	Pressure Sensitive Paint	C_Y	Side force coefficient
S&C	Stability and Control	L/D	Lift over drag ratio
STO	Science and Technology Organization	M	million, 10 ⁶
SWiFT	Swept Wing Flow Test	M_∞	Freestream Mach number
TE	Trailing Edge	P_0	Total Pressure, psia
TWICS	Transonic Wall Interference Correction System	q_∞	Freestream dynamic pressure, psf
UV	Ultraviolet	Re_{mac}	Reynolds number based on mean aerodynamic chord, 10 ⁶
Symbols		S_{ref}	Wing reference area, m ² or ft ²
$\mathcal{R}$	Aspect ratio	T_0	Total Temperature, °F
b	Wing span, mm or in.	y_{dot}	Trip dot height, mils
$\bar{c}$	Mean aerodynamic chord, mm or in.	α	Angle of attack, deg
		β	Angle of sideslip, deg
		η	Span location

I. Introduction

PERFORMANCE tradeoffs in the design of future blended/hybrid wing body (BWB/HWB) and unmanned combat aerial vehicle (UCAV) configurations may result in the selection of lambda wing planforms with leading-edge sweep angles in the region of 50°. These wings typically experience flow separation from leading and/or trailing edges at low to moderate incidence angles due to locally high wing loading and smooth body separation dependence on Reynolds number. The result is undesirable aircraft stability characteristics, which limit the maximum usable incidence and can significantly increase the size and lifecycle cost of the aircraft system. It is therefore critical to be able to predict the maximum usable incidence with high confidence. Otherwise, significant safety margins need to be used, which penalize and increase risk in the design.

Currently, neither conventional low Reynolds number wind tunnel testing nor computational fluid dynamics (CFD), both of which are typically used in the early stages of design, can consistently provide this data at an acceptable level of uncertainty. The AVT-298 research task group[1] was formed to address this problem as part of a collaboration between NASA, the U.S. Air Force Research Laboratory (AFRL), and the U.K. Defence Science and Technology Laboratory (Dstl) under the Applied Vehicle Technology (AVT) panel of the North Atlantic Treaty Organization (NATO) Science and Technology Organization (STO). The Swept Wing Flow Test (SWiFT) research configuration was designed to investigate Reynolds number scaling

effects on low speed stability and control (S&C) characteristics with flow physics relevant to BWB/HWB and UCAV configurations. The configuration primarily comprises a lambda wing planform and a blended center body and wing featuring a 60°/30° leading edge (LE) sweep and a −30°/30° trailing edge (TE)

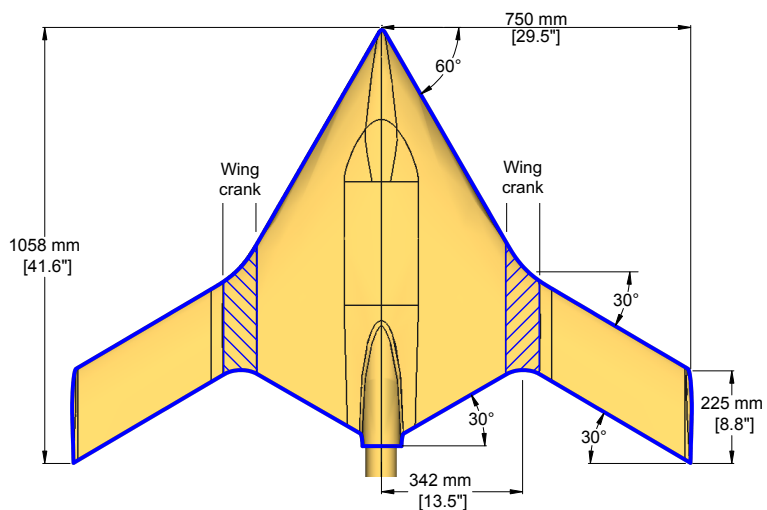


Figure 1. Planform view of SWiFT configuration.

sweep with streamwise wing tips, as shown in Fig. 1. The leading edge and trailing edge near the wing crank region are blended smoothly between the centerbody and wing. The configuration was jointly developed by the AVT-298 task group with Dstl leading CAD development and NASA Langley Research Center (LaRC) incorporating a modern transonic wing design[1]. The centerbody was also thickened to accommodate instrumentation packaging inside the wind tunnel model and the aftbody was modified to accept the support sting and strain gauge balance. A cryogenic wind tunnel model of the SWiFT configuration was designed and fabricated using C200 maraging steel to be tested in both traditional wind tunnel facilities and cryogenic high Reynolds number facilities. To maintain aerodynamic fidelity, the upper surface of the model was kept as smooth as possible, minimizing any steps or fastener holes.

The high Reynolds number wind tunnel test of the SWiFT configuration was conducted in the National Transonic Facility (NTF) at NASA LaRC during the summer of 2023. This paper provides an overview of the NTF test campaign including details on the wind tunnel facility, the test article and instrumentation, the experiment setup and summary, and data results focusing on the force & moment (F&M) data measured by the strain gauge balance. A companion paper focused on the static surface pressure results is described by Chan et al. in Ref. [2].

II. Wind Tunnel Facility

The National Transonic Facility (NTF) [3, 4] is one of a limited number of wind tunnel facilities that can achieve extremely high Reynolds numbers (flight or near-flight) for various aircraft, spacecraft, and launch vehicles [5]. The tunnel is a fan-driven, closed-circuit, continuous-flow, pressurized wind tunnel capable of operating either in dry air at warm temperatures up to 120°F or in nitrogen gas from warm to cryogenic temperatures down to -270°F. The NTF can operate over an absolute pressure range from 1 to 8.3 atmospheres, a Mach number range from 0.1 to 1.2, and a maximum unit Reynolds number of 146 million per foot at Mach 1. Figure 2 shows the major components of the NTF tunnel circuit including photos of the liquid nitrogen (LN_2) injectors and the inlet guide vanes (IGV) and fan blades. The NTF test section has an 8.2 foot square cross section that is 25 feet long. The test section floor and ceiling are slotted (6% open), and the sidewalls are solid.

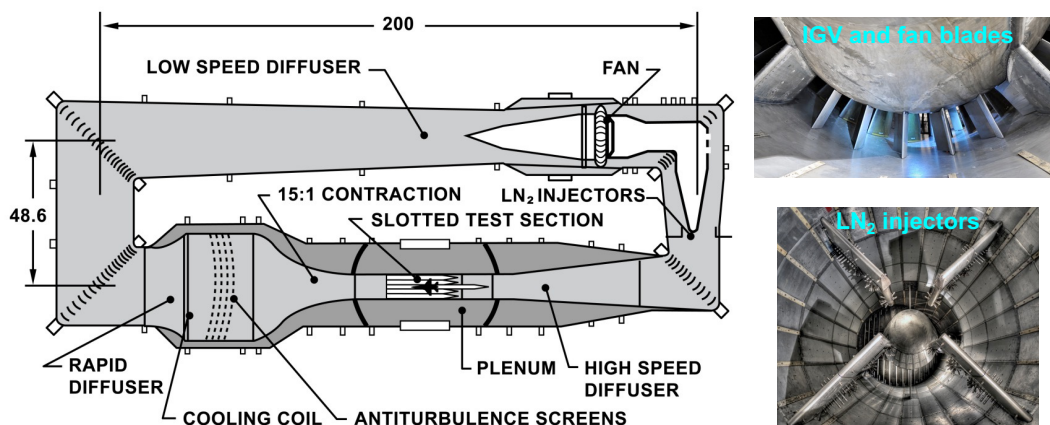


Figure 2. Major components of the NTF tunnel circuit with photos of the LN_2 injectors and the IGV & fan blades. Linear dimensions in feet [Photos: NASA].

III. Test Article Description

The test article is a cryogenic-rated wind tunnel model of the SWiFT research configuration designed and fabricated by the Aircraft Research Association (ARA)[6] in Bedford, England. All of the model components were fabricated using traditional machining methods out of C200 maraging steel in a hardened condition, which is suitable for cryogenic temperatures. Figure 3 shows a computer-aided design (CAD) representation of the SWiFT model as well as a photo of the model in the NTF.

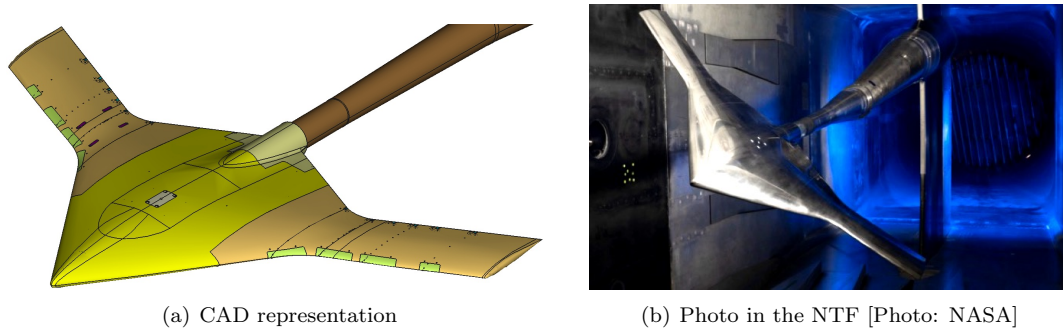


Figure 3. SWiFT model showing (a) CAD representation and (b) photo in the NTF.

The model consists of various components as shown in Fig. 4 with the centerbody and wings being the main components. One of the design criteria was that the upper surface of the model be kept as smooth as possible, with minimal seams or steps between adjoining parts and minimal fastener holes. Therefore, nearly all of the fastener holes for assembly of model part joints and nearly all coverplates are on the lower surface of the model. Similarly, access to the internal volume of the model is from the lower surface. Another design requirement was the inclusion of static pressure orifices on the leading edge and trailing edge of the wings. Due to internal space constraints, this was accomplished through leading edge (LE) or trailing edge (TE) inserts where the static pressure taps were formed in the insert and then the inserts were installed into the wings. The installation of the inserts into the wings were a permanent installation, therefore they were bonded with adhesive before final machining and finishing to fair them in with the surrounding wing surface so that the part seams were nearly imperceptible by sight or feel. Finite element analysis of the wings showed very little deflections under load at the highest loading conditions of the NTF test, therefore the jig shape of the wings were not modified since aeroelastic effects were expected to be minimal.

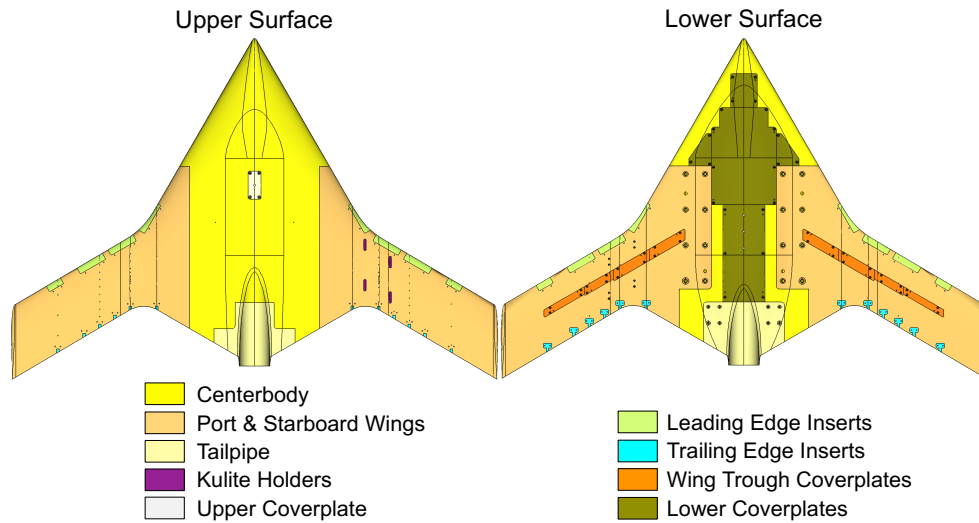


Figure 4. Major components of the SWiFT model.

The reference dimensions for the SWiFT model are shown in Table 1 and are provided in both metric and imperial units. Note that the reference dimensions are based on the entire planform and not just the outer wing sections.

A. Surface Pressure Taps

A total of 126 static surface pressure taps are located along chordwise rows at various span stations on each wing as shown in Fig. 5. For each side (port and starboard), there is one row on the centerbody, one row

Table 1. SWiFT model reference dimensions.

Parameter	Symbol	Metric Units	Imperial Units
Reference Area	S_{ref}	0.6076 m ²	6.5403 ft ²
Reference Chord	$\bar{c}$	559.1 mm	22.012 in.
Reference Span	b	1500 mm	59.055 in.
Aspect Ratio	$\mathcal{R}$	3.703	3.703

inboard of the wing crank region, and three rows on the outer wing. Additionally, there are two stations on the outer wing that just have one tap located directly on the trailing edge or very near to it. Most of the rows contain pressure taps only on the upper surface, but stations 7 and 9 have pressure taps on the lower surface as well. Rows on each side that are at the same station have many pressure taps in identical chordwise locations, but there are some different locations on the upper surface between the port and starboard sides. This is to create a higher density of pressure taps on the upper surface of the wing assuming aerodynamic symmetry between the port and starboard sides. In addition to the static pressure taps on the model, there are also four kulites in the model on the starboard wing only, located in the crank region and the outer wing at stations 6 and 8.1. Each differential pressure kulite is installed and bonded in a special holder assembly and is connected to an adjacent static reference tap in the holder.

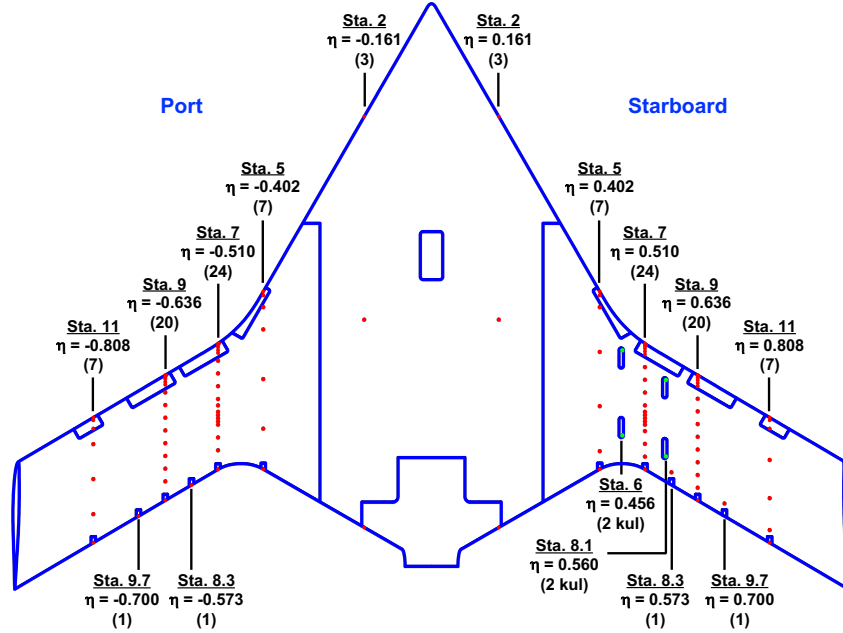


Figure 5. Summary of the SWiFT model surface pressure tap row locations.

B. Boundary Layer Trip Dots

For the majority of the test, trip dots were not applied to the SWiFT model and the boundary layer (BL) was allowed to transition naturally. However, one of the objectives of the test was to assess the effectiveness of BL transition fixing schemes guided by CFD simulations. Therefore, for a handful of low Reynolds number runs, the model was tripped to force turbulent BL development. Several transition fixing schemes were evaluated for both low-speed and transonic Mach numbers with trip dots applied to both the upper and lower surfaces of the model, as specified in Fig. 6 and shown with photos in Fig. 7. Note that the low-speed trip dot locations on the upper surface of the model were very close to the wing leading edge. Trip dot guides were designed and fabricated (3D-printed) by the NTF test engineers to help ensure the placement of the trip dots in the correct locations and to accelerate the process for applying the trip dots to the model.

The location and size of the trip dots for each transition fixing scheme was guided by a hybrid approach described by Luckring et al. [7] that combines CFD simulations with classical test techniques from Braslow [8] and Blackwell [9]. The details of the approach as it was applied to the SWiFT model and a discussion of the NTF forced transition test results are provided by Luckring et al. in Ref. [10].

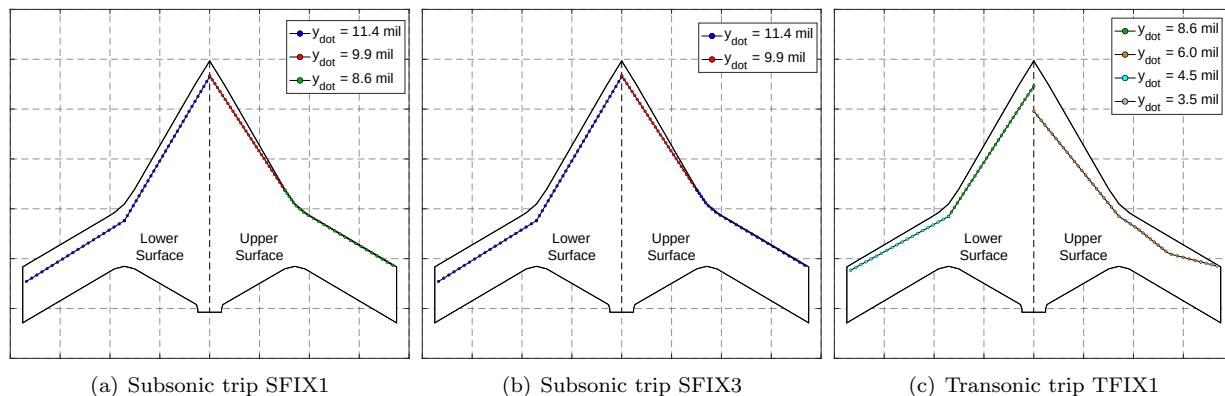


Figure 6. BL trip dot patterns for the SWiFT model test at NTF.

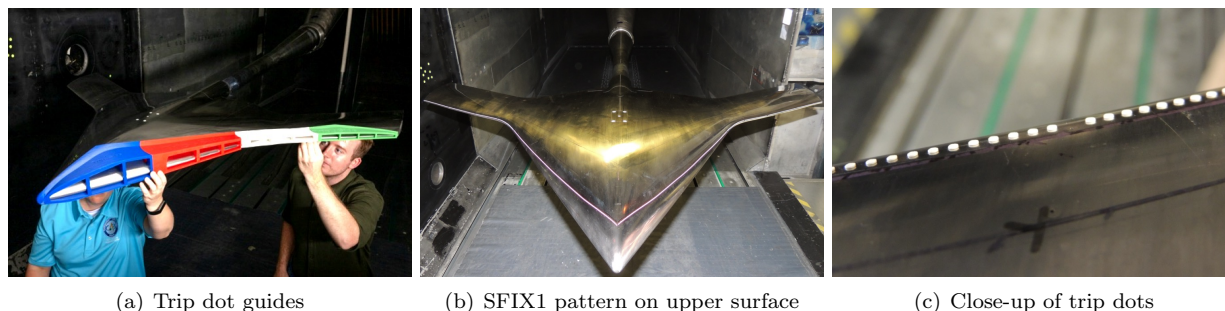


Figure 7. Photo of (a) trip dot guides, (b) SFIX1 pattern on upper surface, and (c) close up of trip dots [Photos: NASA].

C. Instrumentation

A variety of instrumentation were used to measure the quantities of interest during the SWiFT experiment and the locations of the instrumentation within the model are shown in Fig. 8. Model pitch angle was measured with the NTF-204 onboard angle-of-attack (AOA) package that houses two Q-Flex servo accelerometers as well as heaters to survive cryogenic temperatures. Force & moment data were acquired using the NTF-118A balance, which is a one-piece, six-component strain gauge balance, rated for cryogenic temperatures and fabricated from Aermet 100 with a nominal diameter of 2.375 inches. The balance calibration load capacities for the NTF-118A balance are also listed in Table 2.

Two 64-port, 30-psid electronically scanned pressure (ESP) purge modules were used to measure the 126 static surface pressures on the model. The ESP modules were secured inside a copper box with multiple heater elements and placed inside an insulated enclosure to survive cryogenic temperatures. Flexible tubing was used to connect the 0.040-inch (outer diameter) stainless steel tubing of the model to the ports on the ESP modules. The ESP purge modules were required to prevent contamination of the pressure orifices during application of sublimating chemicals or paint formulations by providing a steady air stream to all of the orifices during the application process. Finally, unsteady pressure measurements on the starboard wing were measured by four miniature, cryogenic-rated Kulite® CCL-072 differential pressure transducers with a 15 psid range. For each of the 4 kulites, approximately 1 meter of tubing was installed between the transducer reference and the static tap in the kulite holder to act as a pneumatic filter.

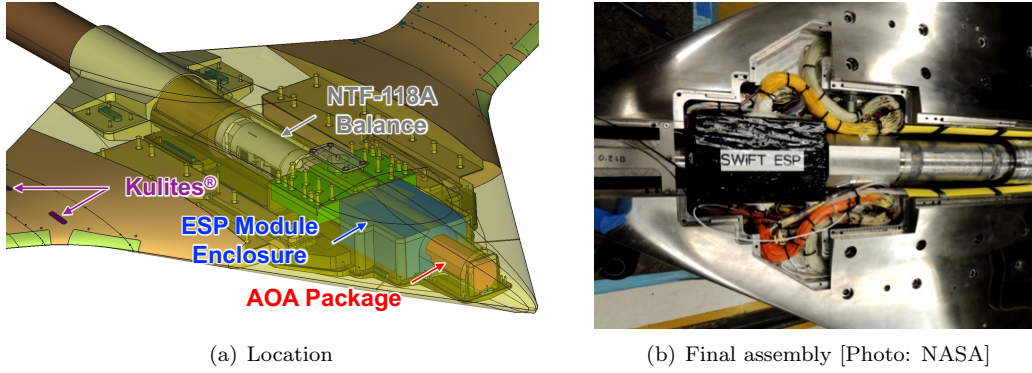


Figure 8. Instrumentation inside the SWiFT model showing the (a) location and (b) final assembly.

Table 2. NTF-118A balance calibration limit loads.

Component	Calibration Load	Model Design Loads	2σ Curve Fit Error
Normal Force	6520 lbf	6500 lbf	± 2.61 lbf
Axial Force	700 lbf	700 lbf	± 0.70 lbf
Pitching Moment	12800 in-lbf	13000 in-lbf	± 6.40 in-lbf
Rolling Moment	8150 in-lbf	9000 in-lbf	± 10.60 in-lbf
Yawing Moment	6400 in-lbf	6500 in-lbf	± 7.04 in-lbf
Side Force	4000 lbf	4000 lbf	± 4.40 lbf

IV. Experiment Setup and Summary

The high Reynolds number test of the SWiFT configuration at the LaRC NTF (Test 232) was conducted from June to August 2023 and was the capstone experiment for the NATO AVT-298 research task group. The main objectives of the test were to investigate Reynolds number scaling effects on the low-speed S&C characteristics as well as the onset and progression of flow separation, evaluate the transonic wing design performance, and assess the effectiveness of BL transition fixing schemes guided by CFD simulations. Additionally, several BL transition detection and flow visualization techniques were performed during the test. Figure 9 shows a photo of the assembled model installed in the NTF test section.

The test covered a range of Mach numbers from 0.2 to 0.8 over a range of Reynolds number based on mean aerodynamic chord from 2.5 to 34 million (M). The tunnel was operated in both air mode and cryogenic N_2 mode over a total temperature range from -200°F to 120°F , a total pressure range from 15 to 100 psia, and a dynamic pressure range from 60 to 1450 psf. Finally, the model was tested over a range of angles of attack from -4° to 20° and sideslip angles from -10° to 10° . The range of test conditions and model orientations are summarized in Table 3.

A summary of the NTF test matrix for the SWiFT configuration is shown in Table 4. The test matrix included baseline testing of the SWiFT model in the clean configuration (no trip dots) at the lowest Reynolds number for each Mach number. These conditions were included to match those at the ARA Transonic Wind

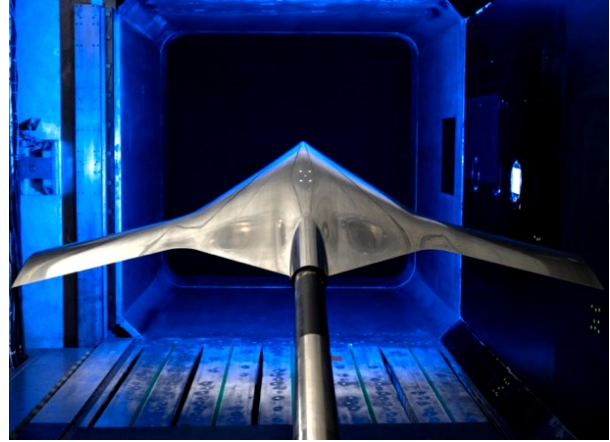


Figure 9. SWiFT configuration installed in the NTF [Photo: NASA].

Table 3. NTF Test 232 SWiFT conditions.

Parameter	Symbol	Range
Mach Number	M_∞	0.2 to 0.8
Reynolds Number (based on mean aerodynamic chord)	Re_{mac}	2.5M to 34M
Total Temperature	T_0	-200°F to 120°F
Total Pressure	P_0	15 to 100 psia
Dynamic Pressure	q_∞	60 to 1450 psf
Angle of Attack	α	-4° to 20°
Sideslip Angle	β	-10° to 10°

Tunnel[11], which is a conventional atmospheric low Reynolds number wind tunnel. The bulk of the test matrix was then dedicated to the investigation of Reynolds number scaling effects at each Mach number with the SWiFT model in the clean configuration. Evaluation of transition fixing schemes and transition detection using sublimating chemicals were performed at the lowest Re_{mac} conditions at $M_\infty = 0.2$ and 0.8. Flow visualization using Pressure Sensitive Paint (PSP) and Femtosecond Laser Electronic Excitation Tagging (FLEET) velocimetry were performed at various Re_{mac} conditions at $M_\infty = 0.2$ and at $Re_{mac} = 16M$ at $M_\infty = 0.8$.

Table 4. Test matrix summary for the NTF test of the SWiFT configuration.

Re_{mac} (10^6)	Mach Number			
	0.2	0.3	0.5	0.8
2.5	✓, T, S, P, F			
3.75	✓, F	✓		
5.75	✓	✓	✓	
7.5	✓, P, F	✓	✓	✓, T, S
11	✓	✓	✓	
16	✓	✓		✓, P, F
24	✓	✓		
34	✓			✓
48				

✓ - F&M / Pressure

T - Transition Fixing

P - PSP

S - Sublimation

F - FLEET

A. Data Acquisition and Data Reduction

Data were acquired via either move-pause or continuous sweep acquisition with model orientation achieved through the NTF arc sector movement (pitch and roll). The move-pause data runs consisted of 8-second averaged data points at a scan rate of 80 Hz for the main NTF data acquisition system (DAS). For continuous sweep acquisition, the model movement rate was 0.1 deg/sec with the same DAS scan rate of 80 Hz. Repeat runs were included throughout the test matrix to assess tunnel and balance data repeatability and reverse direction model traverses were also included to investigate hysteresis effects.

Figure 10 shows the SWiFT F&M data reduction references including the aerodynamic coordinate system, which follows the standard aircraft coordinate system, and the location of the balance moment center (BMC) and moment reference point (MRP). The F&M data were acquired at the BMC and then transferred to the MRP, where the MRP is coincident with the BMC in the x- and y-axes but has a small 6 mm offset in the z-axis. The MRP was chosen to be at the pretest predicted low-speed aerodynamic center of the configuration. Standard NTF F&M data corrections were applied such as balance temperature compensation and interactions, weight tares, flow angularity, cavity pressure corrections, tunnel buoyancy, and wall corrections from the NTF Transonic Wall Interference Correction System (TWICS) software.

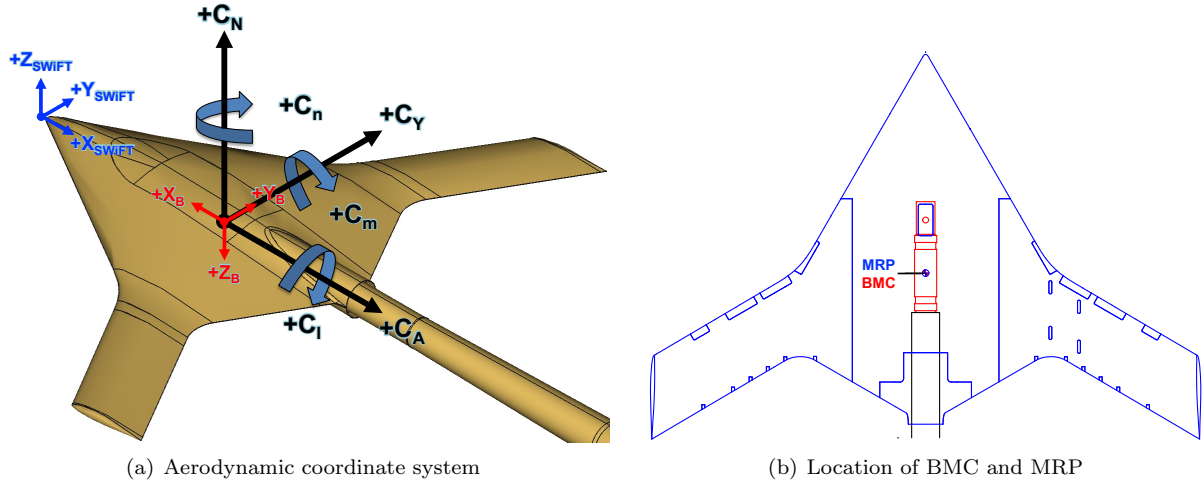


Figure 10. SWiFT F&M data reduction references showing the (a) aerodynamic coordinate system and (b) location of the BMC and MRP.

B. BL Transition Detection

Boundary layer transition detection techniques utilizing sublimating chemicals, static pressure taps, and unsteady pressure transducers were used during the test with the model in a free/natural transition state or a forced transition state using trip dots. The sublimation technique can verify that a transition fixing scheme is working to trip the BL or to determine where natural transition occurs when there are no trip dots applied to the model. This technique requires spraying the model with a sublimating chemical solution and then running the wind tunnel at the desired Mach and Reynolds number condition. The chemical solution (fluorene with Vertrel SDG solvent) in a turbulent BL will sublime faster than in a laminar BL, thereby allowing visual confirmation of BL transition. An example using sublimating chemicals is shown in Fig. 11 for both natural transition and forced transition using trip dots at $M_\infty = 0.8$. Fiducial marks were applied to the model with streamwise spacing of $x/c = 0.1$ to aid in determining the transition location.

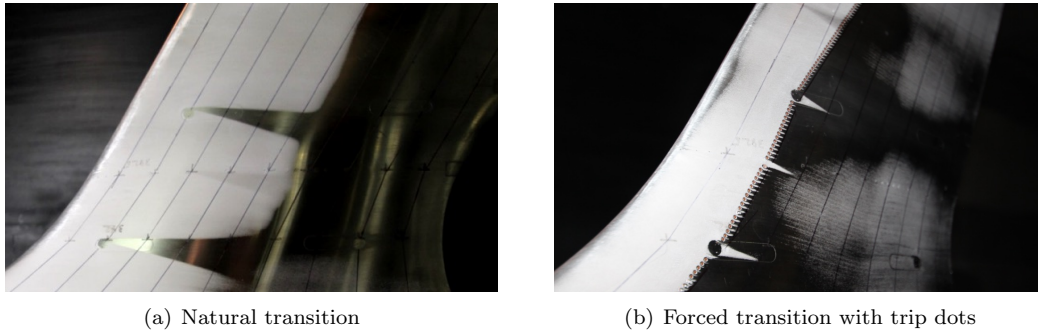


Figure 11. BL transition detection using sublimating chemicals at $M_\infty = 0.8$ for (a) natural transition and (b) forced transition with trip dots [Photos: NASA].

A novel method described by Eppink et al.[12] to estimate the transition location based on static pressure data was also used during the test. The method relies on the fact that the pressure rises slightly when the transition front advances over the sensor. However, with typical pressure tap layouts, this slight rise in pressure is not likely to be observed due to the sparse spacing of the pressure taps. This is rectified by performing continuous sweeps with very fine α -spacing to ensure that the transition front can be observed as it passes over the pressure taps. The unsteady pressure measurements from the kulites were also used to help confirm the transition locations measured using the static pressure data, although only in limited locations. Further details of the various transition detection techniques and a comparison of the results from each technique for the SWiFT model are described by Eppink et al. in Ref. [13].

C. PSP

Pressure Sensitive Paint (PSP) is a technique that allows for measurement of a global surface pressure map on a wind tunnel model and has been used in the NTF in both air mode and cryogenic nitrogen mode in the past[14, 15]. For the NTF test of the SWiFT configuration, the upper surface of the entire model was painted and viewed with two overhead cameras, with one camera on the centerline providing a view of most of the model and a second camera focused on the port wing around the wing crank. Figure 12 shows photos of the SWiFT model during curing of the PSP and also illumination of the PSP under ultraviolet (UV) light. PSP data were acquired at $M_\infty = 0.2$ and 0.8 at several Reynolds numbers in air mode. It was desired to use the cryogenic PSP formulation at the highest Re_{mac} in nitrogen mode, but time and resource constraints prevented it. Further details of the PSP formulations and technique as well as the results from the NTF test of the SWiFT configuration are described by Watkins et al. in Ref. [16].

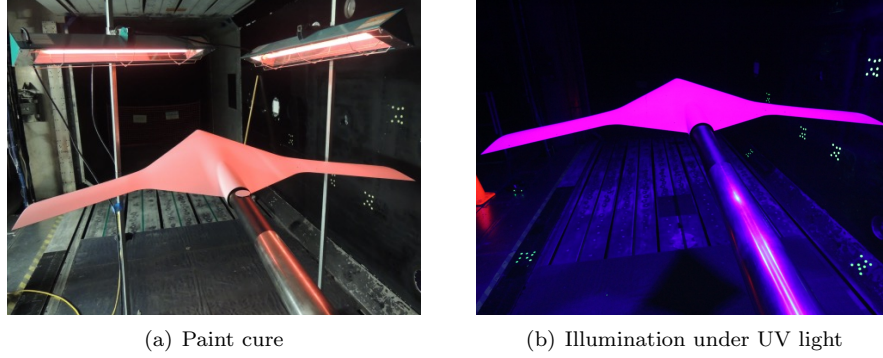


Figure 12. PSP on the model during (a) paint cure and (b) illumination under UV light [Photos: NASA].

D. FLEET

Femtosecond Laser Electronic Excitation Tagging (FLEET) is an advanced velocimetry measurement technique that uses a high-powered femtosecond laser to ionize and dissociate nitrogen gas, and the tagged molecules can then be tracked enabling flowfield measurements. This technique does not require external particle seeding and has been shown to perform extremely well in a pure nitrogen environment. The application of the FLEET technique at the NTF has been in engineering development over a number of years, with some recent demonstrations of its capability described by Reese et al.[17]. The FLEET technique was used in the NTF test of the SWiFT configuration and provided quantitative flow velocity measurements in the wake downstream of the starboard wing crank. The setup and measurement region of the FLEET system during the test is shown in Fig. 13. It was desired to have the measurement region closer to the model, however, limitations in the locations of the laser and cameras in the NTF test section prevented it. Nonetheless, the measurements provided comparison data to CFD and also demonstrated direct correlation to the flow state of the model as it went through stall. Further details of the FLEET technique and the results from the NTF test of the SWiFT configuration are described by Gao et al. in Ref. [18].

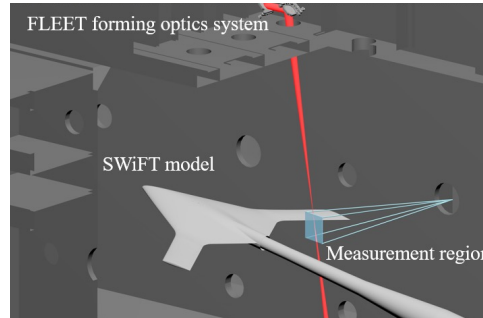


Figure 13. Schematic of FLEET setup in the NTF test section (Ref. [18]).

V. Test Results

The results in this paper will primarily focus on the force & moment data acquired with the strain gauge balance, while a companion paper will primarily focus on the static surface pressure data (Ref. [2]). The F&M results will focus only on the longitudinal aerodynamic coefficients at a sideslip angle (β) of 0 degrees for the SWiFT model in the clean configuration (no trip dots). Furthermore, the focus is mainly on the low-speed results at $M_\infty = 0.2$ and the transonic results at $M_\infty = 0.8$, with limited results at the other Mach numbers. The results use the continuous sweep runs acquired during the test unless otherwise noted. The continuous sweep runs were post-processed by applying a simple 40-sample window average, which produced an averaged data point approximately every 0.05 degrees in angle of attack. For the data plots presented in this section, note that symbols are not drawn at every data point for the continuous sweep runs to reduce clutter and improve readability. Finally, note that the absolute axis scales for the aerodynamic coefficients are redacted in all of the results.

A. Baseline Data and Comparison with ARA Tunnel

In September 2019, after the SWiFT model fabrication was complete, a checkout test campaign[19, 20] was conducted at the ARA Transonic Wind Tunnel with photos shown in Fig. 14. During the test, force & moment data, static surface pressure data, and unsteady surface pressure data were acquired at Mach numbers of 0.2, 0.3, 0.5, and 0.8 and Reynolds numbers of 2.5M, 3.75M, 5.75M, and 7.5M, respectively. Additionally, several BL forced transition schemes using trip dots were tested to compare to the free or natural transition state without trip dots. Finally, several flow visualization techniques were performed including using sublimating chemicals and infrared thermography for BL transition detection, and using ultraviolet oil flow to visualize flow features over the wing and fuselage surfaces. The test served to establish a baseline data set for the SWiFT configuration and allowed for comparison to pretest CFD simulations[21, 22].

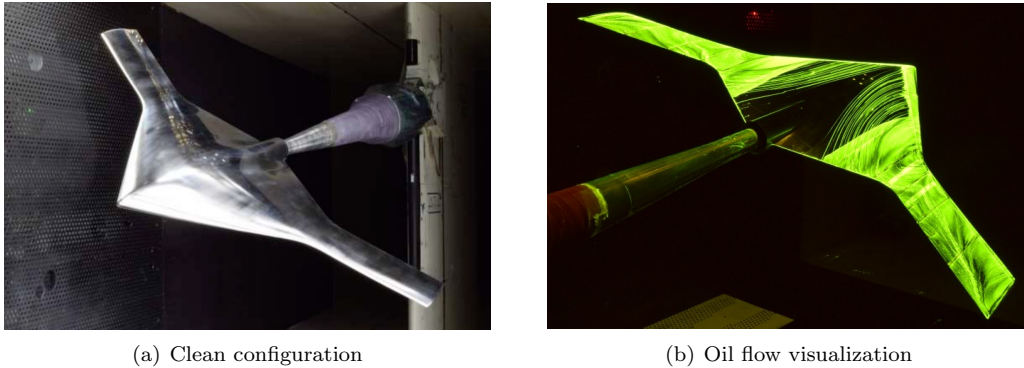


Figure 14. SWiFT model in ARA (a) in clean configuration and (b) with oil flow [Photos: Dstl].

During the SWiFT campaign at NTF, a similar set of baseline data were acquired to compare to the ARA data set and ensure there were no major differences. Figure 15 shows the comparison between the NTF and ARA data sets at Mach numbers from 0.2 to 0.8. The lift coefficient (C_L), pitching moment coefficient (C_m), and drag coefficient (C_D) are plotted against the model angle of attack (α) for each of the Mach numbers, with each column of plots corresponding to a M_∞ and Re_{mac} condition. Overall, the comparison is very good, especially for C_L and C_D . For C_m , the general shape and trend of the curves compare well between the two data sets, but there are small differences at the lower angles of attack for Mach 0.2 and 0.3, and some larger differences after the wing stall and pitch break above $\alpha = 10^\circ$. Error bars for the NTF balance calibration uncertainty are not plotted, but for context, the error bars for C_m are about the size of the symbols at $M_\infty = 0.2$ and 0.3. For Mach 0.5 and 0.8, the NTF data sets could not reach the same maximum angles of attack as the ARA data set due to model dynamics, which prevented capturing the C_m break at Mach 0.8. While the root cause of the differences in C_m at the lower Mach numbers was not determined, the test team was nonetheless encouraged by the good comparisons. The baseline data set at NTF would then be used as the reference in the investigation of Reynolds number effects.

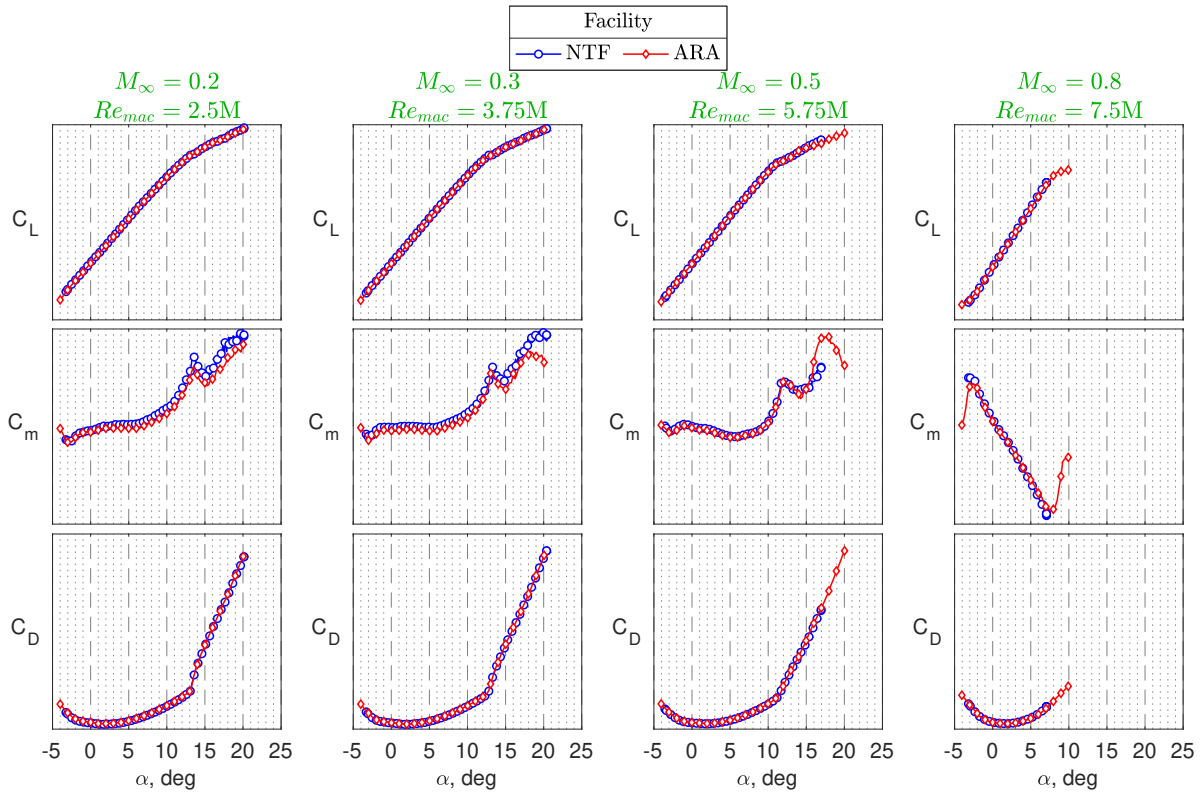


Figure 15. Comparison between the NTF and ARA baseline data sets for $M_\infty = 0.2$ to 0.8 .

B. Continuous Sweep Traverses and Data Repeatability

The initial test matrix for the NTF test primarily consisted of move-pause traverse runs, as that was NTF's main mode of operation. However, for the low-speed runs at $\beta = 0^\circ$, it was desired to capture as much detail as possible around $C_{L,max}$, stall, and post-stall. Therefore, continuous sweep polars were used to ensure that important features were captured that might have been missed with discrete points in a move-pause polar. The issue with continuous sweep polars, however, is determining a sweep rate that is fast enough to be comparable to the time required for a move-pause polar, but slow enough so that a time and pneumatic lag correction can be applied in order to match up with the data from a move-pause polar. Fortunately, it was determined that a sweep rate of 0.1 deg/sec was sufficient to satisfy both criteria and these continuous sweep polars became the main mode of operation during the test for α polars at $\beta = 0^\circ$ at all test conditions.

Throughout the test campaign, the continuous sweep polars were compared against corresponding move-pause polars to ensure that the data sets remained in good comparison. This can be seen in Figs. 16 and 17 for $M_\infty = 0.2$ and 0.8 , respectively. The longitudinal aerodynamic coefficients C_L , C_m , and C_D are plotted against α for the continuous sweep and move-pause polars at various Reynolds number conditions, with each column of plots corresponding to a Re_{mac} condition. For $M_\infty = 0.8$ at $Re_{mac} = 34M$, a continuous sweep polar was not acquired due to time and resource constraints. Overall, the continuous sweep and move-pause data sets compared very well to each other and provided confidence in the quality of the data sets.

Another metric of data quality is data repeatability and therefore, multiple repeat runs were included throughout the test matrix in order to assess the tunnel and balance data repeatability. Figures 18 and 19 show a comparison between repeat move-pause polars at various Reynolds numbers for $M_\infty = 0.2$ and 0.8 , respectively. Again, each column of plots corresponds to a Re_{mac} condition. The repeat runs compare very well with each other providing even further confidence in the quality of the data sets. There were only a few repeat continuous sweep polars during the test and although it is not shown here, the repeatability between them was also excellent.

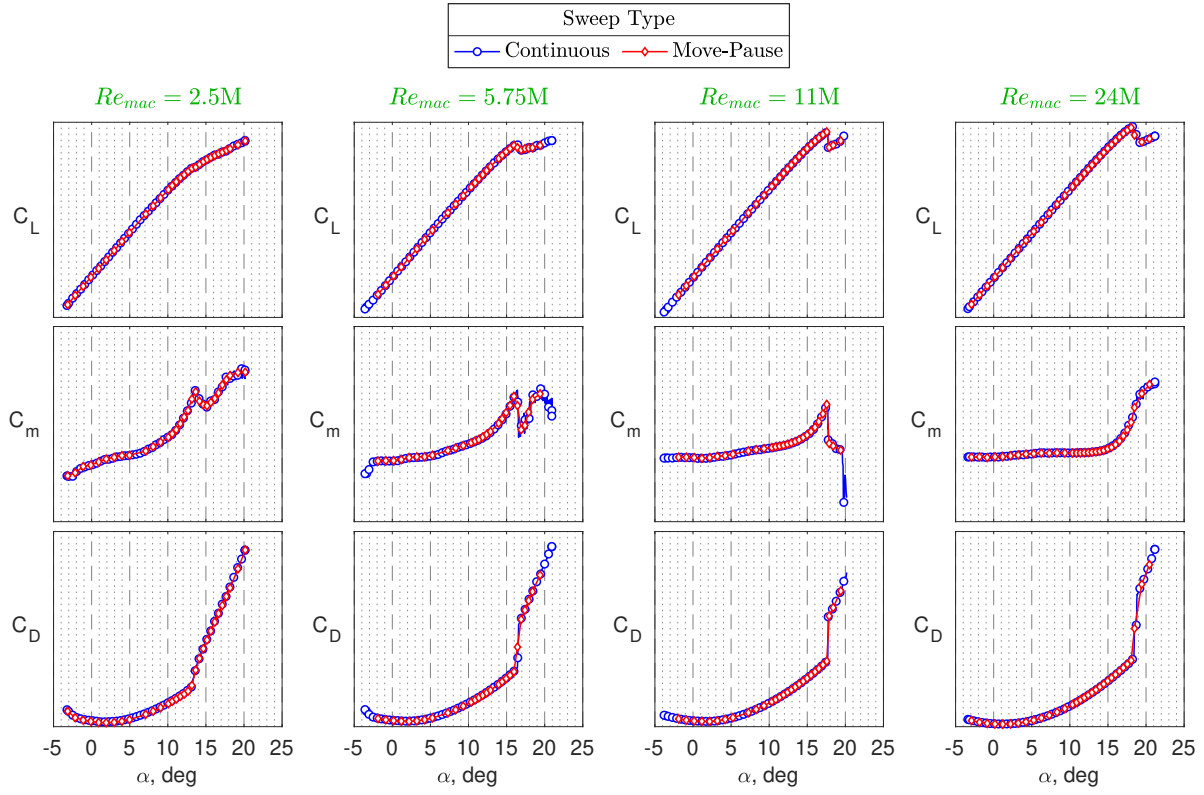


Figure 16. Comparison between NTF continuous sweep and move-pause data sets at $M_\infty = 0.2$.

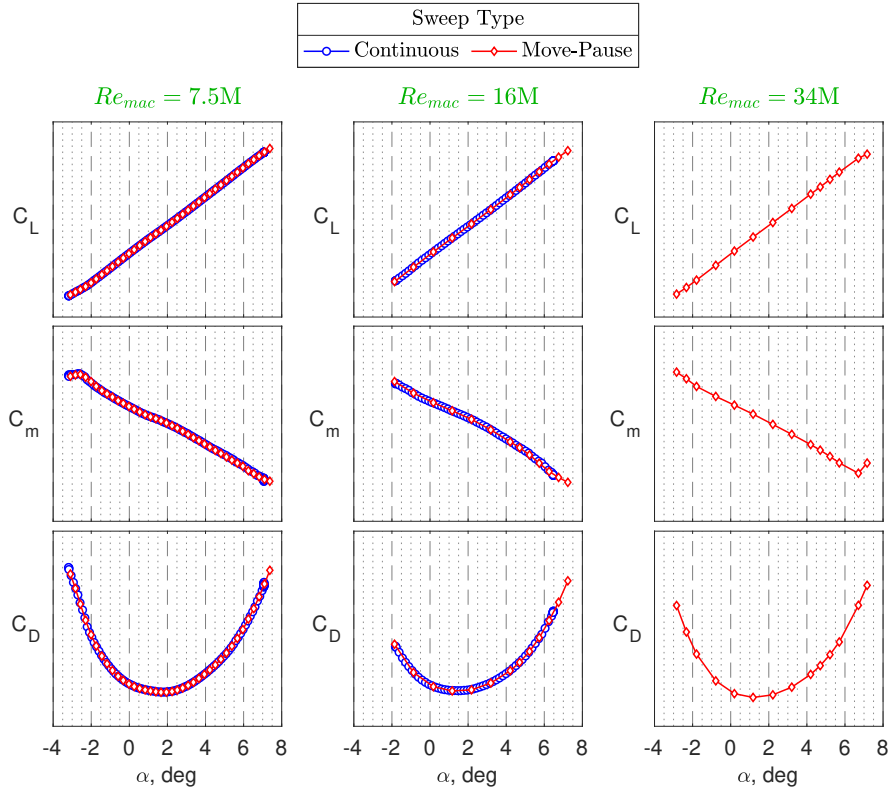


Figure 17. Comparison between NTF continuous sweep and move-pause data sets at $M_\infty = 0.8$.

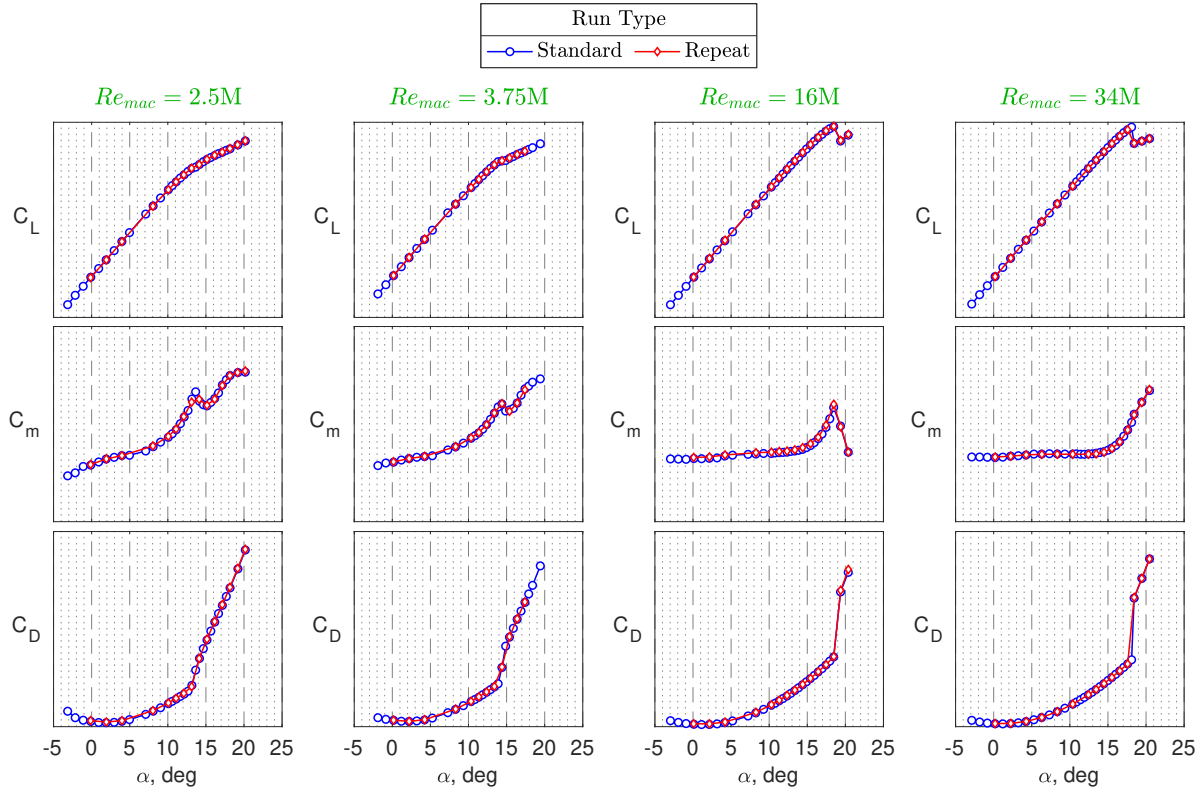


Figure 18. Comparison between NTF repeat move-pause data sets at $M_\infty = 0.2$.

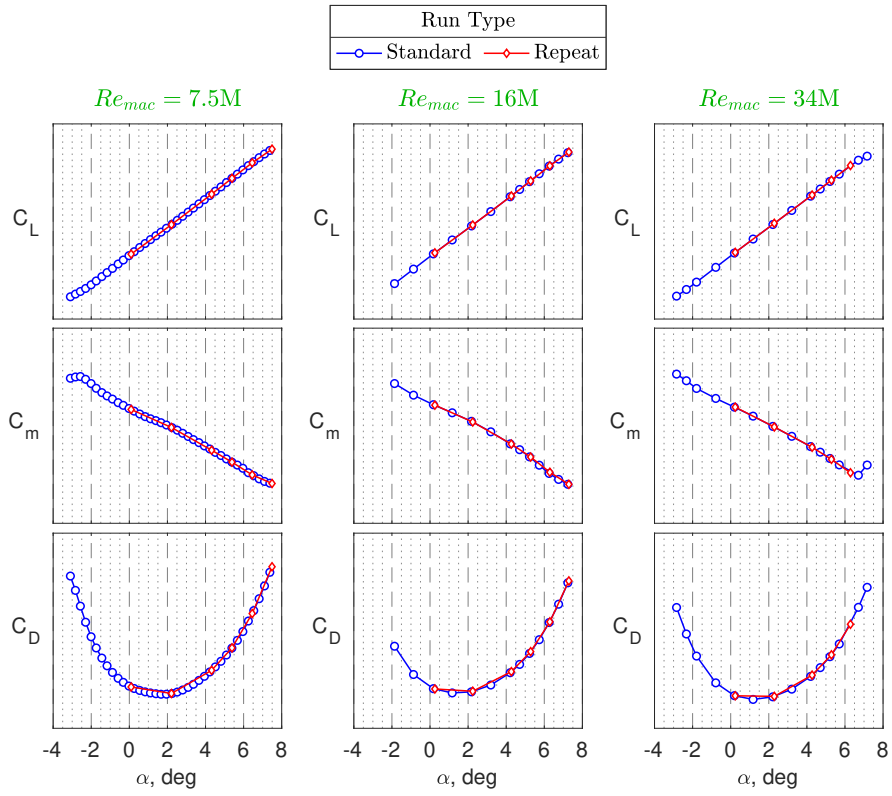


Figure 19. Comparison between NTF repeat move-pause data sets at $M_\infty = 0.8$.

C. Low-Speed Reynolds Number Effects

One of the primary objectives of the test was to characterize the effect of Reynolds number on the longitudinal aerodynamic coefficients at $M_\infty = 0.2$. Figure 20 shows a family of data curves at $M_\infty = 0.2$ for $Re_{mac} = 2.5M$ to $34M$. The longitudinal aerodynamic coefficients C_L , C_m , and C_D are plotted against α in the top row and the increments due to Reynolds number (using the $Re_{mac} = 2.5M$ data as the baseline) are shown in the bottom row. The coefficient scales are redacted, but to provide context on the magnitude of the increments, the range of the increment scales in the bottom row are a percentage of the range of the absolute scales in the top row. For example, the range of the ΔC_L scale is 15% of the range of the absolute C_L scale.

From the increment plots, a couple of observations can be made regarding the effect of Reynolds number. For the lift coefficient, an increase in Re_{mac} produces a slightly lower C_L in the linear portion of the lift curve up to about $\alpha = 8^\circ$, then produces large increases in C_L as the lift curve approaches $C_{L,max}$ and the stall point. An increase in $C_{L,max}$ with increasing Re_{mac} can also be seen and this will be analyzed in more detail in the following paragraph. For the pitching moment coefficient, an increase in Re_{mac} has, in general, a stabilizing effect on C_m for $\alpha > 4^\circ$. Finally, for the drag coefficient, an increase in Re_{mac} produces lower C_D values for all α especially for $\alpha > 12^\circ$ where increased Re_{mac} increases the stall angle and delays increased drag from flow separation over the wings.

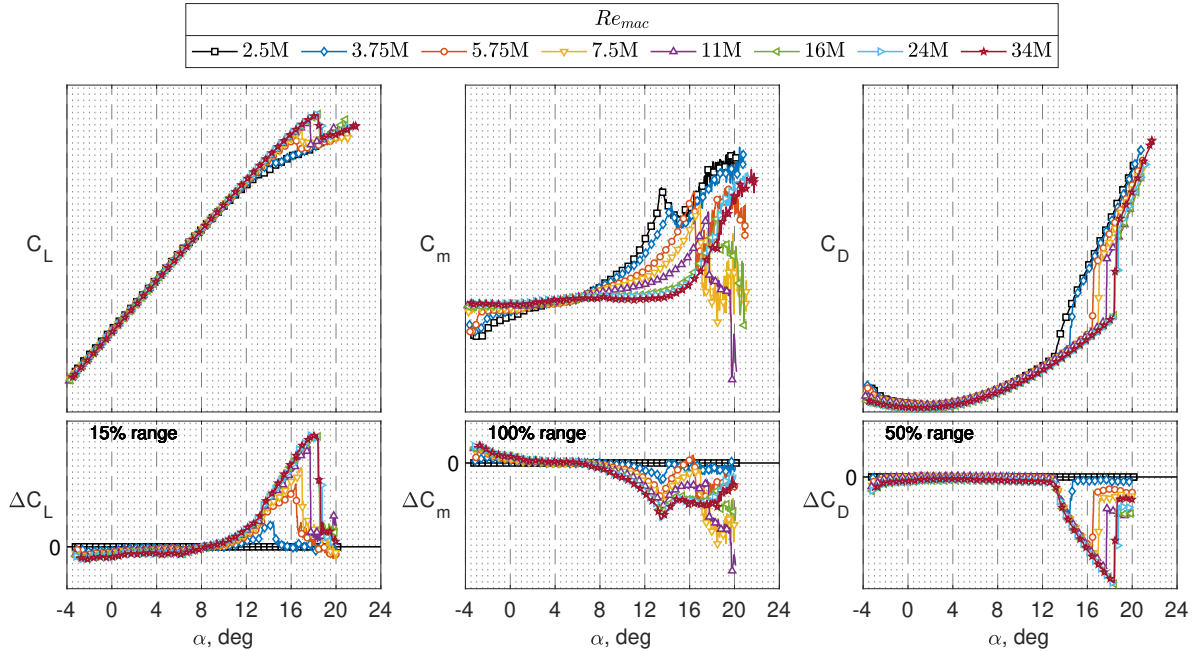


Figure 20. Reynolds number effects on the longitudinal aerodynamic coefficients at $M_\infty = 0.2$.

Figure 21 shows the same family of curves at $M_\infty = 0.2$ for $Re_{mac} = 2.5M$ to $34M$, but zoomed in ($\alpha \geq 12^\circ$) to examine the effect of Reynolds number on $C_{L,max}$. Additionally, the $C_{L,max}$ value at each Reynolds number is displayed with a blue circle as well as the C_m and C_D values at $C_{L,max}$. For most of the Reynolds numbers, the $C_{L,max}$ point matched up with a C_m break, but for $Re_{mac} = 24M$ and $34M$, there was not a visible C_m break. For the baseline run at $Re_{mac} = 2.5M$, there was not an abrupt stall, so it was easier to choose the point where the drag started to increase rapidly to determine $C_{L,max}$. In the bottom row of plots, the values at $C_{L,max}$ are plotted against Re_{mac} to more clearly see the trend with Reynolds number. From these plots, an increase in $C_{L,max}$ and a more abrupt stall is observed as Re_{mac} was increased from $2.5M$ to $16M$, however above $Re_{mac} = 16M$, further increases in $C_{L,max}$ were not observed. For C_m , a decreasing and more stabilizing trend with increasing Re_{mac} is observed and finally for C_D , a similar trend as $C_{L,max}$ is observed (increasing C_D up to $Re_{mac} = 16M$, then no further increases).

To provide more context on the magnitude changes to the values at $C_{L,max}$, the bottom row data is plotted again in Fig. 22, but now as a percentage change from the baseline run at $Re_{mac} = 2.5M$. In addition to the percentage change in the longitudinal aerodynamic coefficients, the α at $C_{L,max}$ is also

shown. The $C_{L,max}$ value increased by over 40% as Re_{mac} was increased to 16M and beyond, and the stall angle (α value at $C_{L,max}$) increased from 13° to over 18° . The increase in $C_{L,max}$ also increased the C_D values at $C_{L,max}$ by about 70% (increased lift-induced drag) and decreased the C_m values at $C_{L,max}$ by over 20% at $Re_{mac} = 34M$.

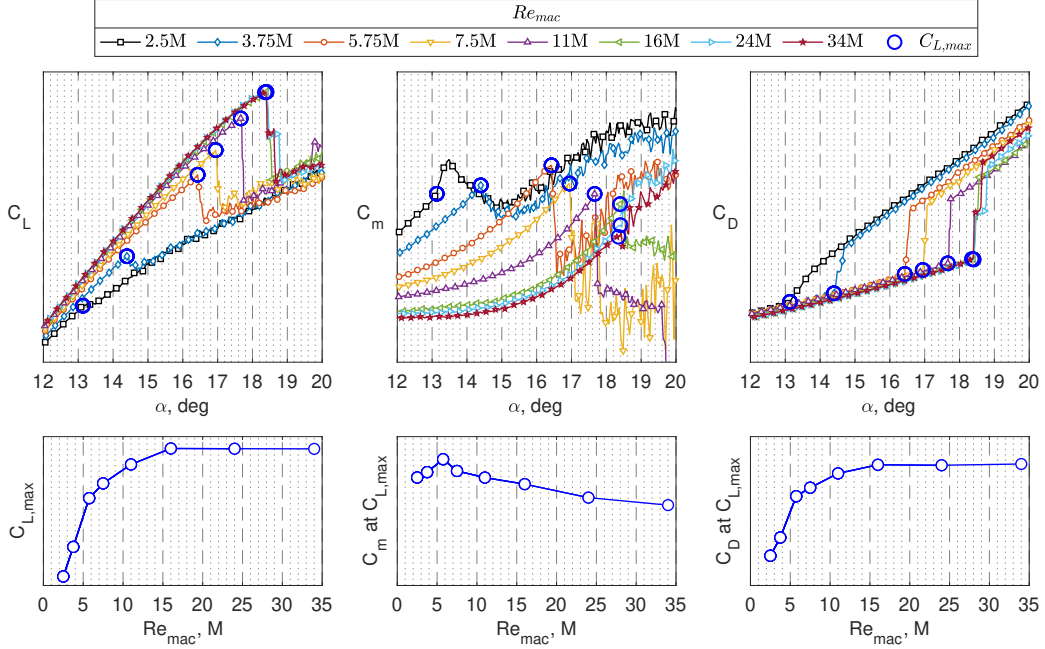


Figure 21. Reynolds number effects on $C_{L,max}$ quantities at $M_\infty = 0.2$.

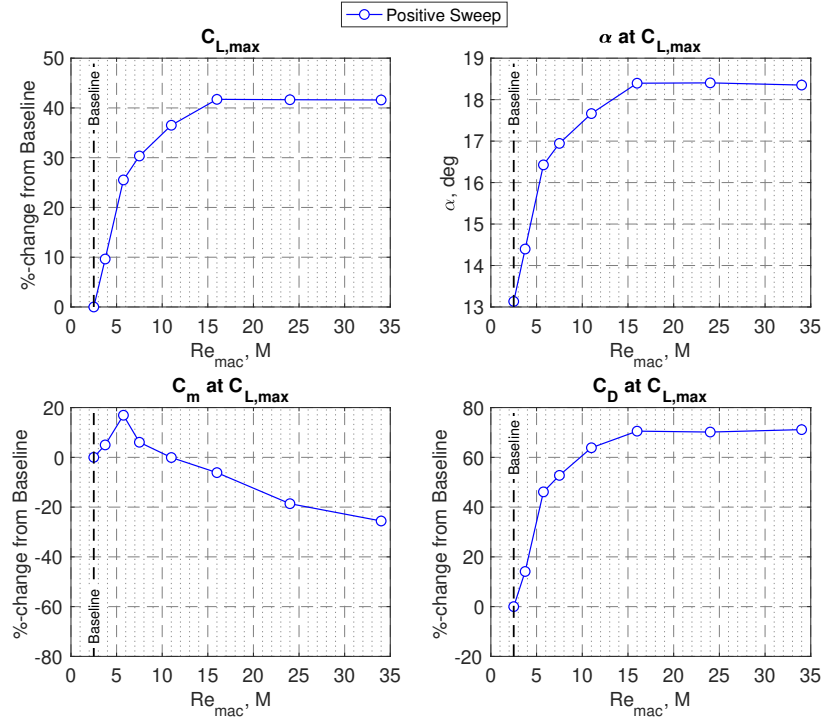


Figure 22. Reynolds number effects on $C_{L,max}$ quantities at $M_\infty = 0.2$ as a percentage change from baseline.

D. Hysteresis Effects

In addition to continuous sweep polars in the positive direction (sweep from minimum α to maximum α), corresponding continuous sweep polars in the reverse direction (sweep from maximum α to minimum α) were also performed during the test to check for hysteresis effects. It was also important to ensure that the negative sweep continuous polars started from a post-stall maximum α and a separated flow state. Figure 23 shows comparisons between the continuous sweep polars in the positive and negative sweep direction at $M_\infty = 0.2$ for $Re_{mac} = 2.5M$ to $24M$ for the longitudinal aerodynamic coefficients C_L , C_m , and C_D . Each column of plots corresponds to a Re_{mac} condition and for each aerodynamic coefficient, the plot scales are the same across the different Re_{mac} conditions with the $C_{L,max}$ values marked for both polars with a black circle. For the baseline runs at $Re_{mac} = 2.5M$, hysteresis effects were not observed as the data from the positive and negative direction sweeps lie on top of each other. However, as Re_{mac} is increased, significant hysteresis effects are observed. While the presence of hysteresis is not surprising due to changing from an attached to separated flow state (and vice versa), the level of hysteresis observed was surprising and shows how sensitive the low-speed aerodynamics are for this configuration.

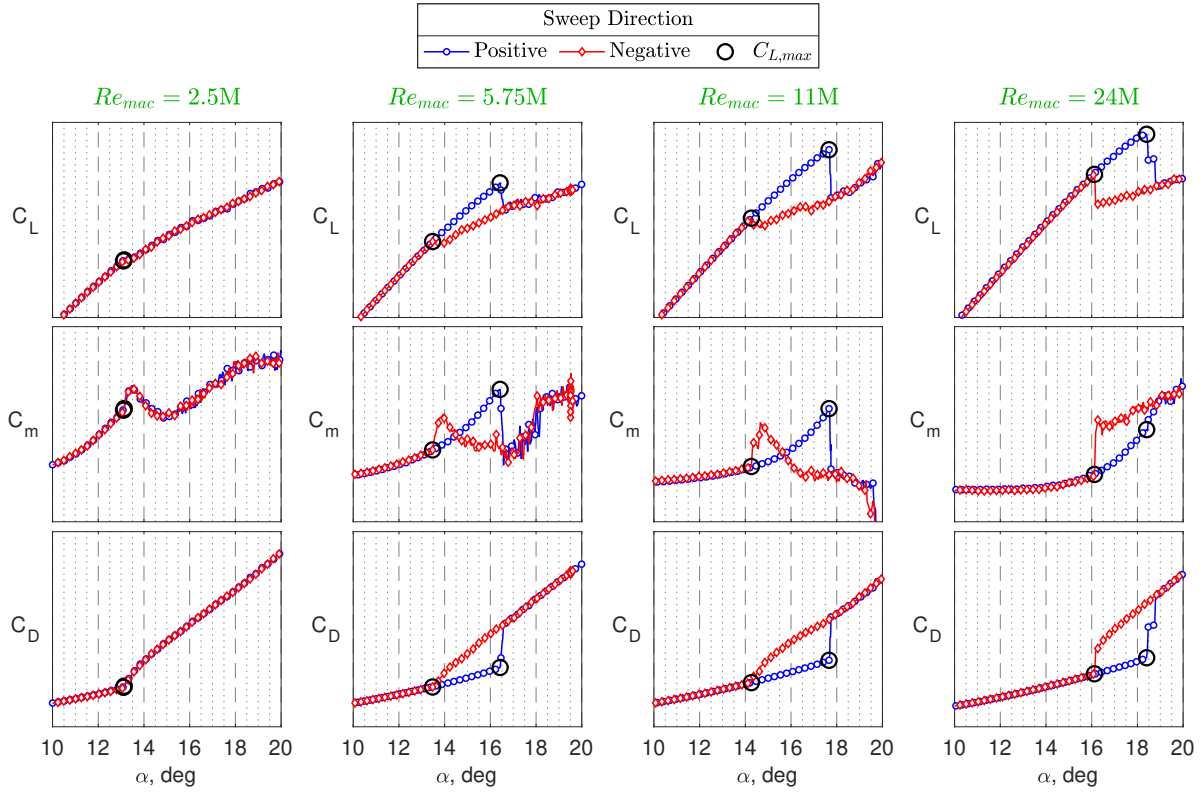


Figure 23. Comparison of positive and negative direction continuous sweep polars at $M_\infty = 0.2$.

Figure 24 shows similar plots as Fig. 21, but for the negative direction continuous sweep polars. The $C_{L,max}$ value at each Reynolds number is displayed with a red diamond as well as the C_m and C_D values at $C_{L,max}$. In the bottom row of plots, the values at $C_{L,max}$ are plotted against Re_{mac} to more clearly see the trend with Reynolds number. All of the plots have the same scales as those in Fig. 21. Although the $C_{L,max}$ quantities for the negative direction polars are much different from the positive direction polars, it still exhibits somewhat similar trends with Re_{mac} .

Figure 25 adds the results from the negative direction continuous sweep polars onto the plots from Fig. 22 for comparison. The $C_{L,max}$ values for the negative direction polars decreased by 10% to 15% compared to the positive direction polars at the highest Re_{mac} conditions ($\geq 16M$) and the stall angle decreased by 2° to 3° at those conditions. The decrease in $C_{L,max}$ for the negative direction polars also produced corresponding decreases in the C_m and C_D values at $C_{L,max}$. These hysteresis results are interesting and might need to be considered when determining the maximum usable incidence of a configuration.

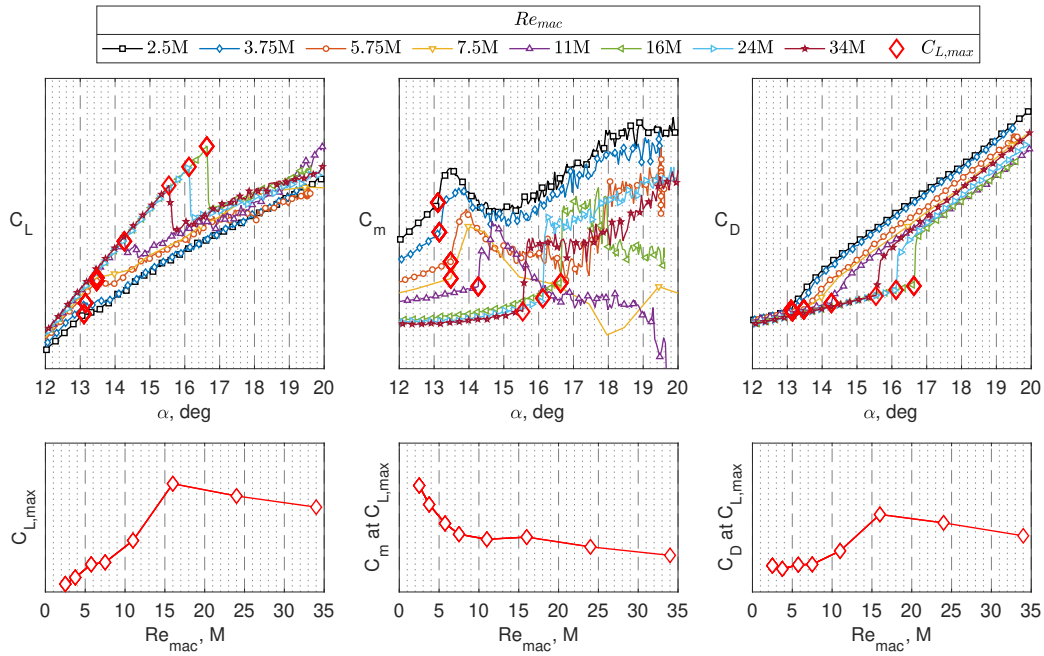


Figure 24. Reynolds number effects on $C_{L,max}$ quantities at $M_{\infty} = 0.2$ (negative direction continuous sweep polars).

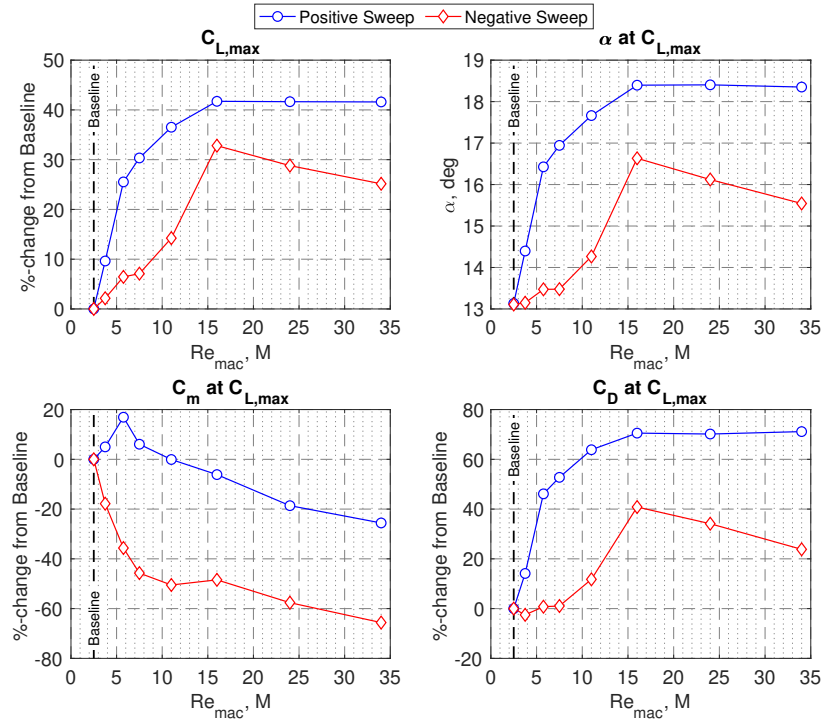


Figure 25. Reynolds number effects on $C_{L,max}$ quantities at $M_{\infty} = 0.2$ as a percentage change from baseline (comparison between positive and negative direction continuous sweep polars).

E. Transonic Performance

Another objective of the test was to evaluate the transonic performance of the NASA LaRC wing design^[1] that incorporated modern supercritical airfoils into the SWiFT configuration. The design point was at M_{∞}

$= 0.8$ and $Re_{mac} = 34M$ at a lift coefficient that roughly corresponded to $\alpha = 5^\circ$ based on pretest predictions. Figure 26 shows the main longitudinal aerodynamic quantities of interest at $M_\infty = 0.8$ and $Re_{mac} = 34M$ with the transonic wing design point shown with a red star symbol. Although the C_L scale is not shown, the design lift coefficient corresponded to roughly $\alpha = 5^\circ$ as predicted. The design point was also pretty close to the maximum aerodynamic efficiency (L/D) measured during the test, which was one of the design goals. Based on these results, the transonic wing design was deemed successful in its goals.

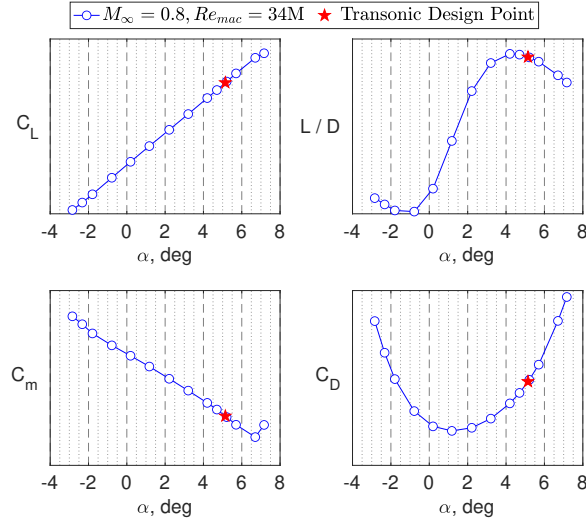


Figure 26. Transonic wing design performance evaluation at $M_\infty = 0.8$ and $Re_{mac} = 34M$.

Similarly to $M_\infty = 0.2$, data were acquired at several Re_{mac} conditions at $M_\infty = 0.8$ to look at the effect of Reynolds number. Figure 27 shows a family of data curves at $M_\infty = 0.8$ for $Re_{mac} = 7.5M$ to $34M$. The longitudinal aerodynamic quantities C_L , C_m , C_D , and L/D are plotted against α in the top row and the increments due to Re_{mac} (using the $Re_{mac} = 7.5M$ data as the baseline) are shown in the bottom row. The range of the increment scales in the bottom row are a percentage of the range of the absolute scales in the top row. For C_L , an increase in Re_{mac} produces a small decrease, while for C_m , an increase in Re_{mac} first shows an increase at $Re_{mac} = 16M$, then a decrease at $Re_{mac} = 34M$. Finally, for C_D , an increase in Re_{mac} produces lower C_D values as expected, which in turn leads to a larger magnitude for L/D .

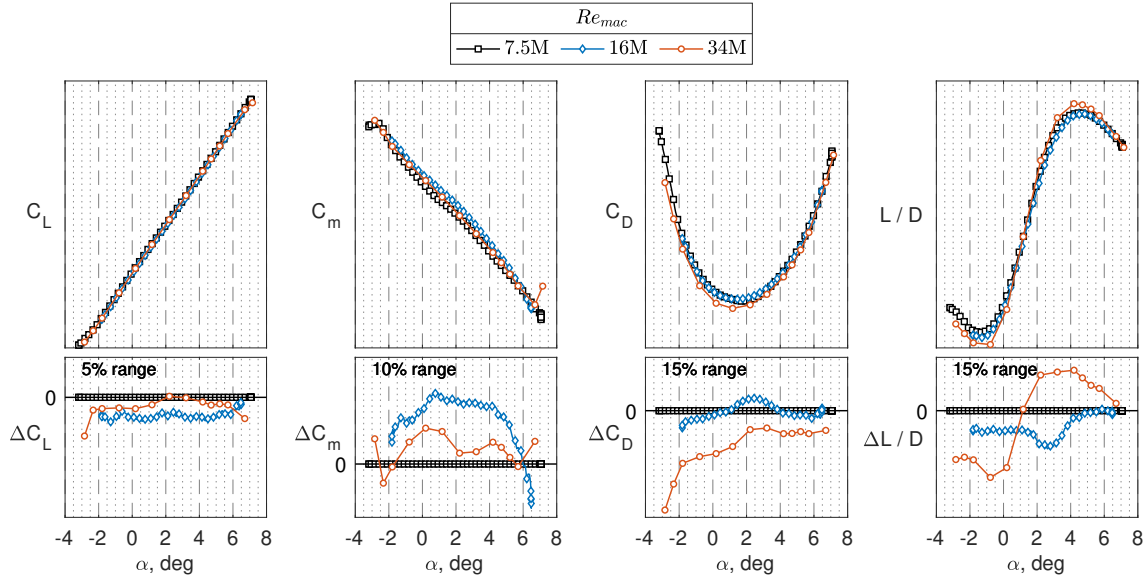


Figure 27. Reynolds number effects on the longitudinal aerodynamic coefficients at $M_\infty = 0.8$.

VI. Concluding Remarks

A high Reynolds number wind tunnel test of the SWiFT configuration was successfully conducted in the National Transonic Facility from June to August 2023 as the capstone experiment of the NATO AVT-298 research task group. The main objectives of the experiment were to investigate Reynolds number scaling effects on the low-speed stability and control characteristics as well as the onset and progression of flow separation, evaluate the transonic wing design performance, and assess the effectiveness of boundary layer transition fixing schemes guided by CFD simulations. Force & moment and surface pressure data were acquired at Mach numbers from 0.2 to 0.8, Reynolds numbers from 2.5 to 34 million, angles of attack from -3 to 20 degrees, and sideslip angles from -10 to 10 degrees. Boundary layer transition detection techniques using sublimating chemicals, static pressure taps, and unsteady pressure transducers were performed during the test, as well as flow visualization techniques including PSP and FLEET.

The paper focused on the F&M results from the test and the baseline low Reynolds number data compared very well with similar data from the ARA Transonic Wind Tunnel. Continuous sweep polars were the main type of run polar used during the test to acquire data over the α range from -4° to 20° at $\beta = 0^\circ$ at all test conditions. The comparison between continuous sweep polars and corresponding move-pause polars were very good throughout the test and the comparison between repeat move-pause polars were also very good, thus providing confidence in the data quality.

Significant Reynolds number effects were observed at $M_\infty = 0.2$ with large increases in $C_{L,max}$ observed with increasing Re_{mac} . Compared to the baseline runs at $Re_{mac} = 2.5M$, the $C_{L,max}$ value increased by over 40% as Re_{mac} was increased to 16M and beyond, and the stall angle increased from 13° to over 18° . However, significant hysteresis effects were also observed when comparing the positive and negative direction continuous sweep polars. Compared to the positive direction polars, the $C_{L,max}$ values for the negative direction polars decreased by 10% to 15% at the highest Re_{mac} conditions ($\geq 16M$) and the stall angle decreased by 2° to 3° at those conditions. Finally, the transonic wing design performance was validated at $M_\infty = 0.8$ and $Re_{mac} = 34M$ with near-maximum aerodynamic efficiency reached at the design lift coefficient.

The data acquired from the test will ultimately help improve computational aerodynamic analysis and design tools for application to future BWB-type vehicle configurations.

VII. Acknowledgement

The international collaboration between researchers across the many organizations comprising the NATO AVT-298 research task group and its subgroup teams was very fruitful and contributed greatly to the success of the NTF experiment. The funding from the NASA AATT, TTT, and SFD projects was very much appreciated allowing for the completion of the experiment even as the test effort suffered from schedule delays and increased costs recovering from the COVID-19 pandemic. Finally, the NTF facility operations were supported by a large team of test engineers, technicians, mechanics, and facility engineers who helped ensure the safe and successful completion of test operations.

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