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An Overview of National Transonic Facility Investigations for High Performance Military Aerodynamics (Invited)

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ABSTRACT

A review of National Transonic Facility (NTF) investigations for high-performance military aerodynamics has been completed. The review spans the entire operational period of the tunnel, and includes configurations ranging from full aircraft to basic research geometries. The intent for this document is to establish a comprehensive summary of these experiments with selected technical results

NOMENCLATURE

C_D	drag coefficient
C_L	lift coefficient
$C_{L,max}$	maximum lift coefficient
C_p	pressure coefficient
$C_{p,le}$	leading-edge pressure coefficient
cbar	mean aerodynamic chord
L/D_{max}	maximum Lift-to-Drag ratio
M	Mach number
q	dynamic pressure
q/E	dynamic pressure divided by modulus of elasticity
Rn	Reynolds number ($\rho ux/\mu$)
Rn_C	Reynolds number based on cbar
Rn_D	Reynolds number based on diameter
r	streamwise leading-edge radius
α	angle-of-attack
θ	angular forebody coordinate, 0 windward

INTRODUCTION

Reynolds number, the ratio of inertial to viscous forces, is the primary aerodynamic scaling parameter used to relate sub-scale wind tunnel models to full-scale aircraft in flight. Reynolds number can have significant effects not only for attached flow properties, such as cruise drag and zero-lift pitching moment, but also for the onset and progression of separated flow effects. With few exceptions, wind tunnel testing is limited to sub-scale Reynolds number conditions, thereby necessitating scaling techniques.

Perhaps the most extensive scaling technology has been developed by the commercial transport industry. Accurate predictions of aircraft aerodynamics such as cruise drag, high lift, and buffet onset are essential due to the competitive nature of that market. This degree of accuracy is often characterized by the interest in knowing configuration cruise drag coefficient to within one count or less ($\Delta C_D < 0.0001$); other metrics are used for high lift etc.

High performance military aircraft historically have not been developed to such stringent aerodynamic requirements, in part due to the inherently multimision nature of these vehicles (e.g., cruise vs. maneuver requirements, clean configuration vs. a variety of load-outs for external stores, etc.) There are none the less a variety of Reynolds number issues of concern to these vehicles.[1] More recently the requirement for low observability has added new constraints to vehicle shaping which results in a compromise with aerodynamics and other disciplines for a successful aircraft design. For these reasons, aerodynamic design is much more of a compromise process for fighter aircraft than for their commercial brethren.

Nonetheless, aerodynamic performance has received scrutiny again from the perspective of program certification. The multimission requirements for fighters are expressed in terms

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of Key Performance Parameters (KPP's) that a proposed vehicle must meet or exceed. Examples include items such as minimum carrier approach speed, non-refueled range, transonic-supersonic acceleration time, etc. It is not uncommon for a fighter to have eight to 10 major KPP's that span very diverse flying conditions. Failure to meet any one of these KPP's can result in program rejustification to the funding sponsors, an activity one is usually loathe to undergo, especially in the current era of extremely tight military budgets. This seems to have moved the need for accurate first-flight fighter performance prediction to be more like that of the commercial transport environment.

In this paper an overview of high-performance aircraft investigations in the NTF is summarized. However, a brief background of the NTF is first reviewed and juxtaposed with the evolving research environment as the facility was brought on line. This is followed by a summary of the fighter projects that have used the NTF along with some concluding remarks. The reader is also referred to a much broader review of military aerodynamic contributions[2] performed at the NASA Langley Research Center

BACKGROUND

Facility

The National Transonic facility was pioneered in the 1970's as a unique means to achieve full-scale Reynolds number and Reynolds number effects in a transonic wind tunnel for a broad class of configurations. Facility construction began in 1979, and an initial shakedown phase of operations was initiated in 1982. Facility calibrations and practical experience in facility operations and safety were gained during this phase but there were very limited opportunities for research applications. As operational experience was gained, the need for research applications continued to grow, and in 1990 a redirection of the facility toward research applications and needs was initiated.

The combination of research customer needs with the prior operational experience for this new and complex facility led to a major facility productivity enhancement that was implemented in 1997. Current research application entries are balanced with a variety of customer-driven facility operations research activities to address overall facility capability[3] and test execution process, flow characterization[4] and data uncertainty[5], semispan testing techniques[6] and low-speed wall interference technology[7], and a variety of models/instrumentation technologies.[8-10] Fuller[11] has documented basic facility operations, and a more complete historical perspective has been published by Wahls.[12] The facility is shown in Figure 1.

Fig. 1- National Transonic Facility (NTF).

The NTF can be operated at Mach numbers ranging from 0.2 to 1.2, total pressures from 1.2 to 8.8 atmospheres, and total temperatures from around 120° F down to minus 250° F, the cryogenic temperatures being achieved through the evaporation of injected liquid nitrogen.

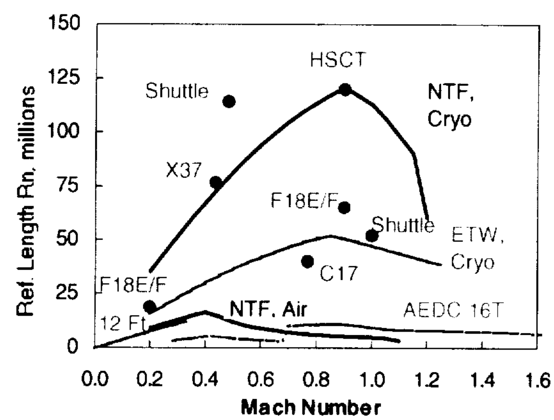


Fig. 2- Facility envelops.

An overall Mach-Reynolds number facility envelope is presented in Figure 2 for NTF (both air and cryogenic modes) and compared with several other facilities. Facility Reynolds numbers are based on one-tenth the square root of the test section area. Also shown for reference are a variety of slender vehicles at various flight conditions along with the C17 as a representative military transport.

There are two key capabilities for this facility. The first is the capability to obtain high Reynolds number data at near- to full-scale conditions. This greatly reduces or eliminates any extrapolation for sub-scale Reynolds number effects. The ability to obtain Rn effects data at elevated Reynolds numbers also greatly enhances the scalability of these results to even higher conditions.

Perhaps of comparable importance to the high Reynolds number capability, though, is the capability to independently vary one aerodynamic parameter (e.g., Reynolds number) while holding two other parameters (e.g., Mach number and the dynamic pressure) constant. This is possible due to the independent control of flow speed, total pressure, and total temperature in NTF. One could just as well vary q/E while holding M and Rn constant, so Reynolds number and static aeroelastic effects can be isolated. These effects are inherently coupled in a conventional pressure tunnel, and can be one source of pseudo Reynolds number effects. For the slender-wing configurations of this paper this is not as great an issue as it is for high aspect-ratio configurations.

Research Environment

The fall of the Berlin Wall in 1988 led to a basic change in the country's investment strategy for military research, including aerodynamics. As one consequence, much of the military aerodynamic research from the 1980's was significantly scaled back by the time NTF was being shifted toward research applications around 1990.

The use of the NTF for military aerodynamics was also affected by a fundamental programmatic shift within NASA toward precompetitive commercial aeronautics during the 1990's. This work was embodied in two focused programs: (i) the High Speed Research (HSR) program[13] which was initiated in 1990 and directed at supersonic commercial transport technology, and (ii) the Advanced Subsonic Technology (AST) program which was initiated in 1994 and directed at subsonic commercial transport technology. These program commitments also coincided with a substantial downsizing of the federal government as mandated by the Clinton-Gore administration. All of this resulted in a significant reduction in workforce commitments for military aerodynamics during the 1990's. For the NTF, the consequence was a greatly reduced program from what had been planned in the early 1980's. Both of the focused programs were terminated in 1999 due to budget priorities.

RESULTS AND DISCUSSION

There have been twelve tests in the NTF that relate to high-performance military aerodynamics, and the tests occurred between 1985 and 1999. For this report the tests have been grouped as follows: Aircraft Configurations, Advanced Concepts, Research Configurations, and Basic Research Geometries.

Aircraft Configurations

Four high-performance aircraft configurations have been tested in NTF from 1985 to 1993. Two of the tests used NTF as a conventional pressure tunnel to leverage existing (non-cryogenic) wind tunnel models; the other two tests exploited the cryogenic capability with new models. The tests have addressed both cruise and maneuver aerodynamics; they have contributed to wing design validation, vehicle certification for flight, and ground-to-flight data-base development. All four tests were done as part of broader collaborative ventures.

EA-6B – A collaborative effort among the US Navy, Grumman Aircraft Systems, and NASA Langley (LaRC) was conducted during the 1980's to improve the maneuver capability of the EA-6B aircraft.[14] This work was done as part of the Navy's Advanced Capability Program (ADVCAP) for the EA-6B. The EA-6B had grown to a 45,500-pound (maximum landing weight) airplane as compared to its 36,000-pound progenitor, the A-6, with very little change in wing characteristics to accommodate this 25% weight growth. One consequence of this weight growth was a sixty percent reduction in maneuver stall margin at 250 knots for a 2-G turn.

To reduce this deficiency, a constrained wing design activity[14] was performed computationally. Modifications were restricted to the leading-edge slat and trailing-edge flap which had to fair smoothly into the existing wing geometry. The design was focused on improving low-speed high-lift capability while maintaining transonic cruise performance. Numerical results indicated that the basic design objectives could be met.

A 1/16th scale version of the EA-6B aircraft was tested in the NTF in the fall of 1985. The purpose of the test was to verify the high Reynolds number computational wing design improvements on high-lift performance with the different wing flap/slat modifications. The test program was focused at M=0.3 and Rn_c from 1.4 to 5.4 million (nearly flight) at angles of attack from -8° to 20° with realistic wing stores configuration. Limited data were also obtained up to supersonic Mach numbers of 1.1. A pre-existing wind tunnel model was used for this investigation, and therefore the test was done in air only, with Reynolds number changes being achieved through changes in total pressure from nominally 1 to 4 atmospheres. As a consequence aeroelastic effects were not determined. A photograph of the model installed in the NTF is show in Figure 3.

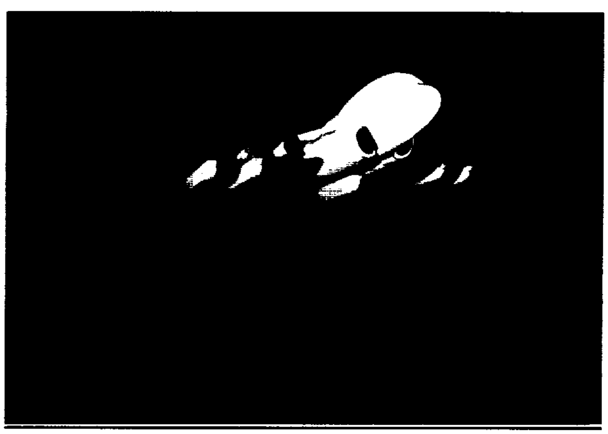
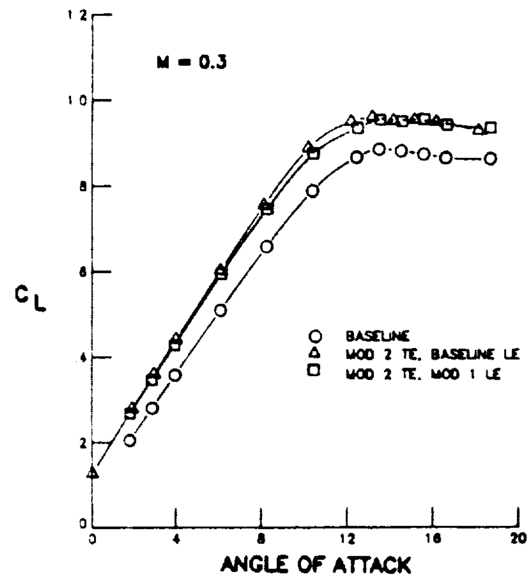
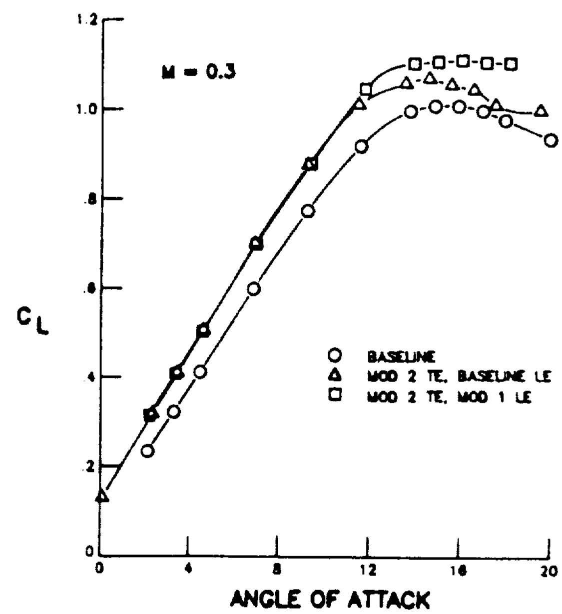


Fig. 3- EA-6B configuration.

Experimental results from this investigation are shown in Figure 4. While the flap effects were comparable at both low and high Reynolds number, the additional lift increment due to the leading-edge slat was only evidenced at the high Reynolds number condition. This lift improvement would have been missed had only the conventional Reynolds number data been available. Although both Reynolds number and dynamic pressure were simultaneously being varied through the total pressure, it was felt that this slat lift increment was primarily associated with Reynolds number effects as opposed to model aeroelastics.



a) Rn_c = 1.4 x 10^6



b) Rn_c = 5.4 x 10^6

Fig. 4 – EA-6B Reynolds number effects on high-lift increments, M = 0.3. (Circle = baseline, Triangle = baseline + flap mod, Square = baseline + flap mod + slat mod)

The net lift improvement was about 11% near $C_{L,max}$ and about 25% in maximum useable lift. Although not shown, the wing modifications also produced a transonic drag reduction over a large portion of the aircraft's operating envelope. The experimental results verified the numerical predictions.

Flight tests of a modified EA-6B also verified these improvements, but fiscal constraints and other programmatic issues prevented the Navy from implementing these and other vehicle improvements to the fleet.

F-14 – As part of an extensive viscous drag reduction activity[15,16] a research project was spawned in the 1980's to assess the interaction effects between Cross-Flow (CF) and Tollmien-Schlichting (TS) instabilities on boundary-layer transition in the context of Natural Laminar Flow (NLF). It was well known that these interactions could cause transition to occur under otherwise favorable conditions. Data were needed to assess the effects of wing pressure distribution, Reynolds number, and wing sweep on boundary-layer transition as induced by the CF-TS interaction. This led to the Variable Sweep Transition Flight Experiment (VSTFE), a collaborative effort among LaRC, the Grumman Aerospace Corporation, NASA Dryden, and Boeing. The F-14 aircraft was selected as a test bed for its variable sweep capability, and two NLF wing gloves were designed.[17,18] To save costs, the program called for gloving only one wing and flight certification data were needed for this asymmetric configuration of the aircraft.

In support of this program need, a 1/16th scale version of the F-14 was tested in the NTF in the fall of 1985. The purpose of the test was to obtain flight certification data for NLF glove effects on the F14 aircraft. The glove was only on one semispan of the vehicle. Data were obtained from M=0.20 to 0.90 and Rn_c from 0.8 to 2.5 million at angles of attack from -4° to 20°. The model is shown in Figure 5.

Program schedule did not permit for fabrication of a cryogenic wind tunnel model, so an existing transonic model was used for the test with NTF operating as a conventional transonic pressure tunnel. Model load restrictions prevented high Rn testing, but the data were considered sufficient for the intended flight certification objective, and the asymmetric vehicle was deemed flight worthy. The NTF data were not published and unfortunately appear to be unrecoverable.

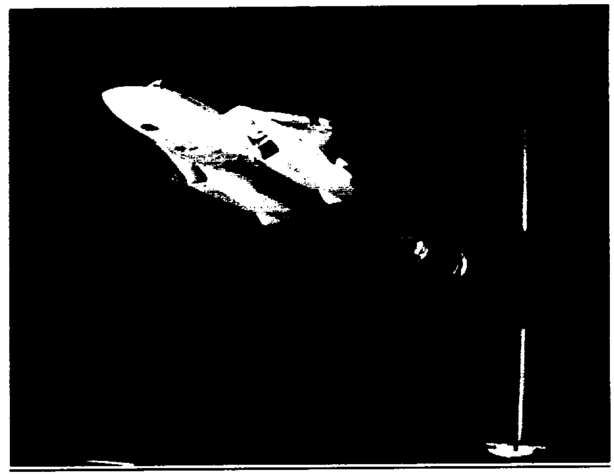


Fig. 5- F-14 configuration.

Flight tests were performed in 1986 and 1987 at NASA Dryden with NASA 834, an F-14 Navy Tomcat. Figure 6 shows this aircraft with the left semispan gloved to achieve laminar flow. The flight test program was successful, first in establishing the desired laminar flow in flight, and second in quantifying by a number of measurement techniques[19] the CF-TS interaction transition process for a variety of wing sweep and flow conditions.

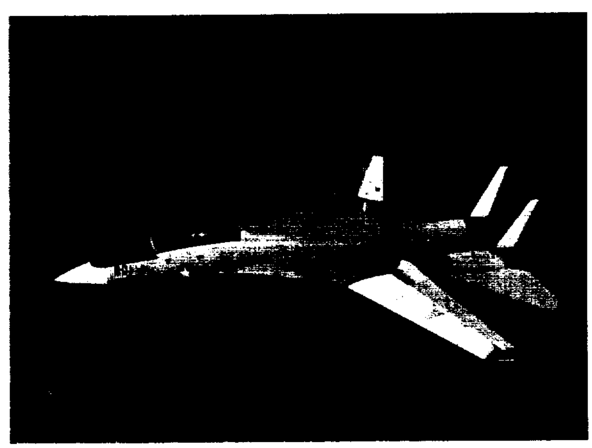


Fig. 6– F-14 flight test with NLF wing glove.

X-29 – In the 1980's NASA and the Grumman Aerospace Corporation embarked on a program to assess forward sweep design for fighter aircraft.[20,21] This work had its origin in Defense Advanced Research Projects Agency (DARPA) sponsorship,[22] and resulted in the X-29 research aircraft. First flight occurred at NASA Dryden in 1984, and a second aircraft, targeted at high-alpha research, was initially flown in 1989.

To leverage this flight program, a cryogenic wind tunnel model of the X-29 was fabricated for ground-to-flight correlation studies of Reynolds number effects. A 1/16th scale version of the X-29 aircraft was tested in the NTF in the spring of 1992. The purpose of this test was to determine the Reynolds number effects on forebody pressures at high angles of attack, and compare NTF high Reynolds number data to flight measurements. Forebody pressure data were obtained from M=0.22 to 0.25 and Rn_c from 0.7 to 6.8 million (flight) at angles of attack from 30° to 66°. In addition, limited data at M=0.6 and Rn_c from 1.6 to 8.4 million were obtained at angles-of-attack from 30° to 40°. A photograph of the model and the high angle-of-attack support mechanism is shown in Figure 7.

Fig. 7- X-29 NTF configuration on high-α sting.

The data showed significant Reynolds number effects on forebody pressure distributions. An example is presented in Figure 8, from Ref. 23. Here the lowest or conventional Reynolds number results (Rn_D=0.3x10^6) show a laminar-like forebody separation, whereas all the higher Reynolds number results (0.9x10^6<Rn_D<2.4x10^6) exhibit turbulent characteristics. After this change

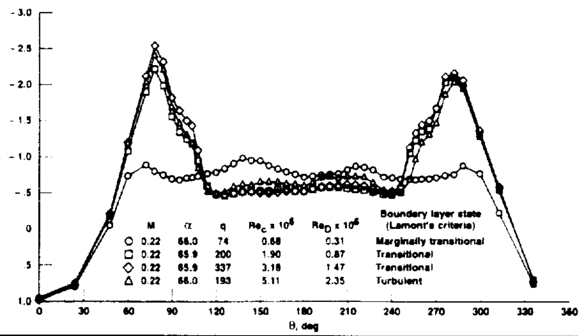


Fig. 8- NTF X-29 forebody pressures, from Ref. 23. M = 0.22, α = 66°.

of separation state, the Reynolds number effects are small. It is fairly common for conventionally sized models to exhibit transitional forebody flows. In addition, forebody flows that exhibit turbulent separation characteristics at moderate angles of attack can of course become transitional at very high angles of attack due to the increased influence of the cross-flow plane on the forebody flow physics.[24] Hence, Reynolds numbers based on a characteristic length such as forebody diameter become more meaningful at these conditions.

The high-α research vehicle is shown in Figure 9 with forebody flow visualization being used to relate forebody vortical structures to the surface pressures.

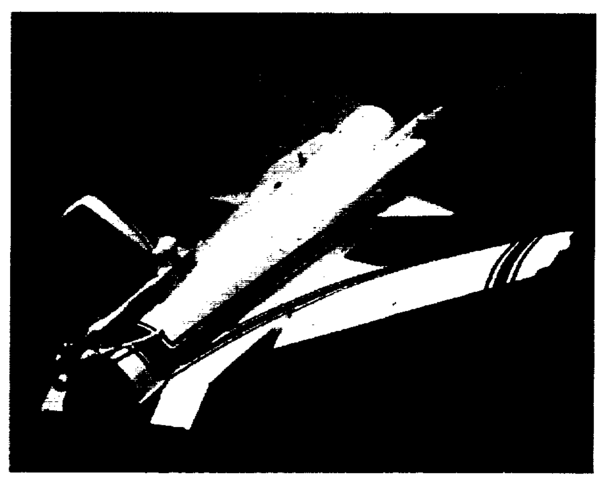
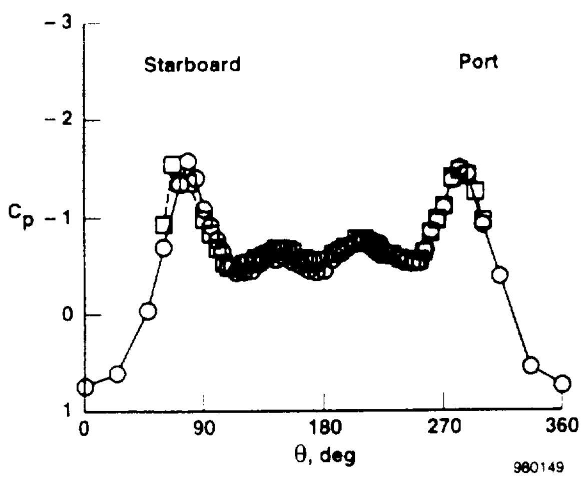


Fig. 9- X-29 high-α research vehicle

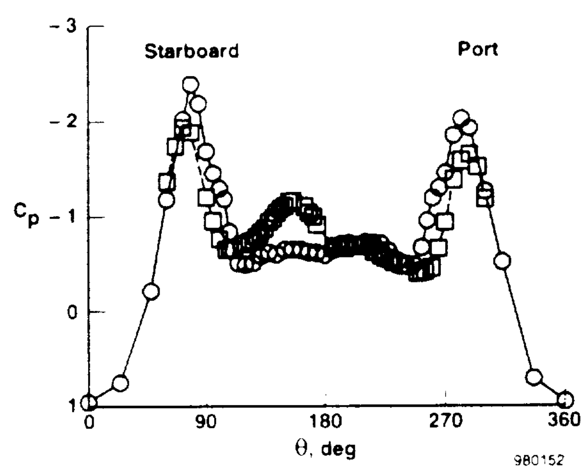
Comparisons between the high Reynolds number NTF data and the flight results are presented in Figure 10. The comparisons were very good up to approximately 50°. This also corresponded to conditions where the forebody flow remained essentially symmetric. It is clear that the low

Reynolds number wind tunnel results (Figure 8) would not match flight at all.

Above 50° the forebody pressures exhibited asymmetry in both data sets, with the flight results showing a stronger leeward suction peak than the wind-tunnel results. This discrepancy could have been due to differences in either the forebody strake geometry or the forebody surface finish; the NTF model was much smoother than the aircraft. Correlation of the forebody pressures and flow structures to high angle of attack aircraft properties has also been published.[25]



a) $\alpha = 50°$, $Rn_c = 5.6 \times 10^6$, $Rn_D = 2.6 \times 10^6$



b) $\alpha = 66°$, $Rn_c = 5.2 \times 10^6$, $Rn_D = 2.4 \times 10^6$

Fig. 10- X-29 tunnel to flight comparisons, from Ref. 23. M = 0.22. (Circle = NTF, Square = Flight)

Alpha Jet – In the fall of 1986 a cooperative program was initiated between the US Air Force and the German Ministry of Education and Science, Research and Technology to acquire a unique data set for tunnel-to-tunnel and ground-to-flight studies of high Reynolds number aerodynamics[26]. This work was focused on the Dornier Alpha Jet to leverage data from a prior collaboration that included conventional Reynolds number wind tunnel results as well as flight data supplied by Dornier to the USAF. Tests for the new collaboration were performed in the Arnold Engineering Development Center (AEDC) 16T and 4T tunnels, the NASA NTF, and the German Kryo-Kanal Koln (KKK) facility. The tests were all done with a new wind tunnel model that was fabricated for cryogenic conditions.

As NASA's part of this activity, the 1/10th scale version of the Alpha Jet was tested in the NTF in the summer of 1993. The purpose of the test was to develop a Reynolds number effects data set for ground-to-flight and facility-to-facility correlations. Data were obtained from M=0.20 to 0.90 and Rn_c from 3 to 24 million (flight) at angles of attack from -4° to 11°. The model, installed in NTF, is shown in Figure 11.

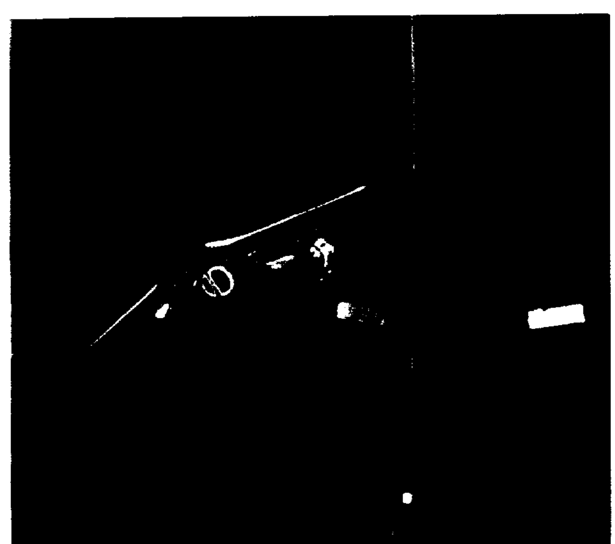


Fig. 11- Alpha jet configuration in NTF.

Only limited analysis of these results has been performed, and the data set is unpublished but available. Some results were included in Laster's Reynolds number scaling paper.[27]

Advanced Concepts

Three advanced concept configurations were tested in NTF from 1985 to 1990. All of these activities were collaborative. The models were fabricated for conventional pressure tunnel testing and were not suitable for cryogenic testing. Most of the results from all three tests are still restricted for national security purposes and cannot be discussed. However, some aspects of a B-2 test[2] can be reported.

B-2 - A 3.2-percent scale version of the B-2 aircraft was tested in the NTF in the spring of 1986. The purpose of this test was to assess Reynolds number effects for extreme-α aerodynamics (up to 85°), provide data to assess and validate results from low Reynolds number B-2 spin tests, and to update pre-flight stall characteristics, control effectiveness, and α limit in association with pitch-up.

Data were obtained from M=0.10 to 0.85. At M=0.23 the data spanned Rn_c from 2 to 15 million (25% low-speed flight) at angles of attack from -4° to 85°. The high-speed data were limited to lower angles of attack. A photograph of the model on the high-α sting support is shown in Figure 12.

Fig. 12- B-2 configuration on high-α sting.

Due to the restricted nature of this program NASA was precluded from documenting or publishing results from these activities.

Research Configurations

Early in the planning for research programs for the NTF, it was decided to include several research configurations known as Pathfinders. These would be used to gain experience with Reynolds number effects from the NTF on configurations relevant to industry interests, but not so specific as an actual aircraft configuration. Pathfinder I configurations were transport like, and were further supplanted by the configurations tested under the AST focused program. The Pathfinder II series were fighter-class configurations, and two of these were developed collaboratively with industry in the 1980's. Testing did not occur until later in the 1990's due to the aforementioned history of the facility.

A total of three research configurations were tested in NTF from 1992 to 1999. Two of these were part of the Pathfinder program executed jointly between NASA and industry; both of these models were cryogenic. The third configuration was part of a collaborative effort among NASA, the US Navy, and the Defense Evaluation Research Agency (DERA) of the United Kingdom. Among these three Reynolds number programs, wing control-surface effects, empennage effects, and high-lift effects were explored.

GD Pathfinder II - This configuration was developed jointly with the General Dynamics Corporation (Ft. Worth, Texas), now Lockheed-Martin. The model included a conventional (smooth-sided) forebody and an advanced, moderately swept and cambered diamond wing with parametric leading and trailing edge devices. The leading and trailing edge flaps were designed

Fig. 13- General Dynamics Pathfinder II configuration.

in conjunction with the wing camber to meet a range of performance goals. The model was designed for cryogenic testing. A photograph of the model is shown in Figure 13.

Tests were performed in the NTF in the spring of 1992. The purpose of the test was to quantify Reynolds number effects on force and moment properties up to high angles of attack. The primary configuration variables were leading-edge and trailing-edge flap settings. Data were obtained from M=0.40 to 0.95 and Rn_c from 5.4 to 66 million (flight) at angles of attack from -3° to 33°.

A limited and unpublished analysis of these data indicated an adverse Rn effect on drag due to lift that was unanticipated; further analysis of the data set was also recommended. The data from the NTF test are unpublished, but data and analysis from supersonic testing of this configuration have been reported[28].

<u>MDC Pathfinder II –</u> This configuration was developed jointly with the McDonnell Douglas Corporation (St. Louis, MO.), now Boeing. The model had a conventional (smooth-sided) forebody, an advanced cambered transonic wing, and a variety of empennage components. This model was also designed for cryogenic testing.

Tests were performed in the NTF in the fall of 1995. The purpose of the test was to provide a full-scale Reynolds number data base and

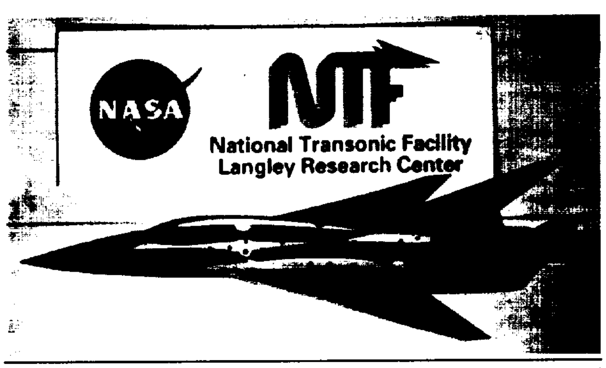


Fig. 14- McDonnell-Douglas Pathfinder II configuration.

Reynolds number increments applicable to thin-wing, fighter-type configurations. Data were obtained from M=0.60 to 0.90 and Rn_c from 5 to 61 million (flight) at angles of attack from -2° to 18°. A photograph of the model is shown in Figure 14.

Limited analysis of these data has been documented,[29] and a sample result on L/D_{max} is shown in Figure 15. The data show an appreciable effect on L/D_{max}, and in addition demonstrate a reversal of the compressibility effect on L/D_{max} over the range of Reynolds numbers shown. Among these data, however, dynamic pressure is also changing, and thus it is unclear how much of the effects shown are strictly due to Reynolds number as opposed to static aeroelastics. Results such as these would benefit from further analysis to discern the relative flow physics contributions to these changes. There was also a recommendation for further study of lateral-directional Rn effects.

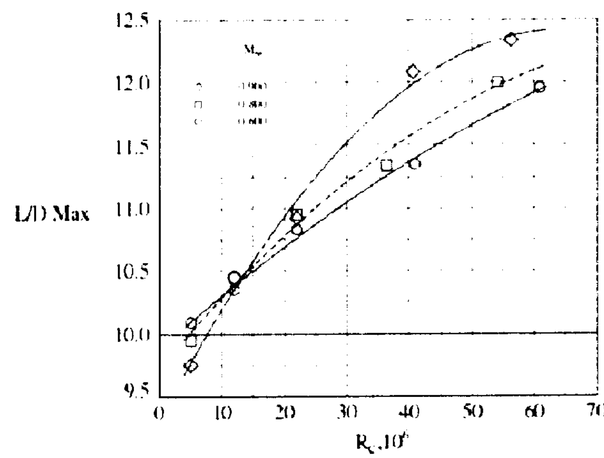


Fig. 15- Mach and Rn effects on maximum L/D

<u>Diamond Wing –</u> A cooperative program among the Naval Air Warfare Center Aircraft Division (NAWCAD), DERA, and NASA was conducted to explore high-lift aerodynamics of an advanced wing concept at conditions representative of carrier approach and launch. The collaboration was facilitated under the auspices of The Technical Cooperation Program (TTCP), and included wing design activities, CFD analysis studies, two wind tunnel models, and testing in both the DERA 5m tunnel and the NTF.

The diamond-wing semispan model was tested in the NTF in the fall of 1999. The purpose of the test was to quantify the low-speed high-lift aerodynamics of an advanced and observably constrained wing planform suitable to carrier operations. Data were obtained from M=0.10 to

0.35 and Rn_c from 4 to 24 million (flight) at angles of attack from -5° to 25°. These tests were done with the test-section slots closed to increase the high-lift data quality, and this had a side benefit of reducing facility consumables by approximately one third. A photograph of this model is shown in Figure 16.

The model incorporated a simple leading-edge flap with a more complex trailing-edge high lift system comprised of a closely coupled shroud and fowler-type trailing-edge flap. The principle configuration parametrics were the flap and shroud incidence settings along with the high-lift rigging (gap and overlap). Model static aeroelastic deformations were measured and found to be small. The aeroelastic measurement targets can be seen in Figure 16.

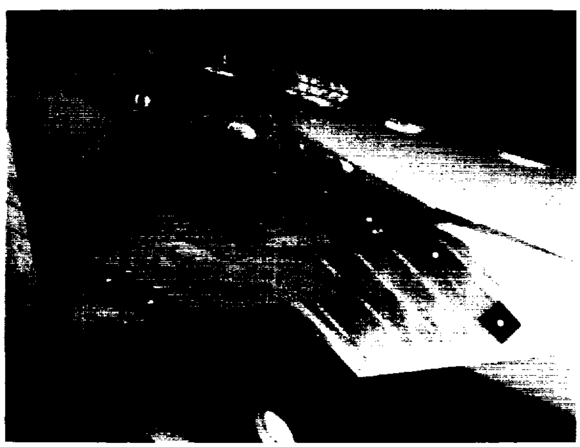


Fig. 16- Diamond wing semispan model in NTF.

The data set from this investigation is quite extensive, and some preliminary analyses of the high-lift results[30] and Reynolds number effects[31] from this experiment have been recently published.

One noteworthy aspect of this investigation was that data representative of full-scale Reynolds number conditions were easily achieved. The model was designed for conventional pressure-tunnel testing and was not cryogenic. However, the combination of about 6 atmospheres with a semispan test (large chord) of a low aspect ratio configuration (even larger chord) resulted in Reynolds numbers typical of carrier approach for an F18 E/F wing. The NTF envelopes, based on this diamond wing model, are presented below in Figure 17 along with the same slender aircraft reference points.

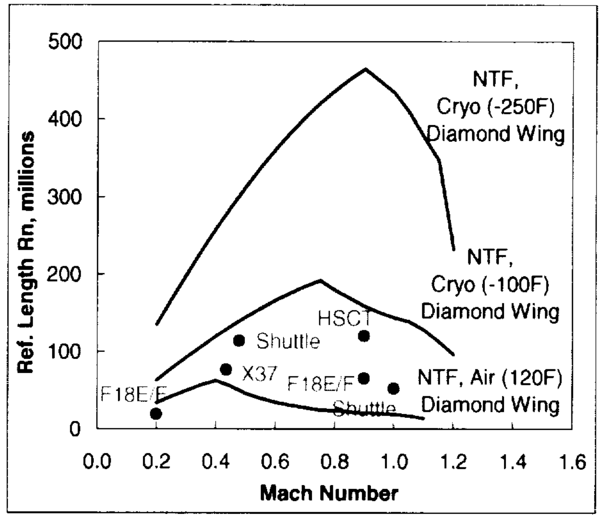


Fig. 17- Semispan test capability for slender vehicles.

The figure also shows a nominal cryogenic condition, -100F, which encompasses all the vehicle performance conditions. To be practical, the testing of such large models would probably preclude the higher-speed test conditions, but nonetheless low-speed to moderate-speed full scale Reynolds numbers could be rather easily achieved with the semispan test technique for a suite of low aspect ratio configurations. Most of these configurations typically have small model aeroelastic effects.

Basic Research Geometries

An additional dimension to the early planning (ca. 1980) for NTF research programs was to include several basic research geometries. These would be used to gain a more fundamental understanding of Reynolds number effects on basic flow structures pertinent to various vehicle-class aerodynamics. It was also anticipated that such simple shapes would be useful to the emerging Computational Fluid Dynamics capability to integrate the Euler and Navier-Stokes equations numerically. This activity resulted in plans to study fundamental separation onset and progression phenomena from basic shapes such as an isolated forebody or a delta wing. Execution of these plans was delayed during the 1980's while operational experience with NTF was gained.

Two basic research configurations were tested in NTF from 1990 to 1991 that pertain to military aerodynamics. The first was a systematic set of forebody geometries that reflected the shift toward chined shapes. The second was a delta wing with variable leading edge bluntness. A third basic research investigation of skin friction[32] was also performed in 1996 with a modified tangent-ogive circular cylinder. Although the results of this study are generally applicable, the work was motivated primarily by the commercial transport sector and will not be further discussed in this report. Only the forebody study was noncryogenic.

Fabodies – Fighter forebody design underwent a fundamental change to meet low-observable requirements. After decades of experience with smooth-sided forebody evolution, the forebody was redesigned to account for radar cross section requirements, essentially a mutation to chined or otherwise sharp-edged forebodies. The early plans to study smooth-sided forebody aerodynamics were similarly mutated to become a parametric study of chined forebody geometries referred to as faceted bodies, or Fabodies for short.

Fig. 18- Fabody configurations.

These geometries were tested in the NTF in the fall of 1990 and are shown in Figure 18. The purpose of the test was to determine Reynolds number effects on forces, moments, and pressures for this family of advanced forebody geometries up to high angles of attack. The models were designed for cryogenic conditions but only tested in the pressure mode. Forebody force and pressure data were obtained at M=0.20 and Rn_D from 0.4 to 3.6 million (flight) at angles of attack from 0° to 27°.

The NTF data have been analyzed and published.[33] These same models were tested over a much broader angle of attack range at subsonic atmospheric conditions,[34] and they were also tested at supersonic conditions.[35] Although all of these data have been analyzed and published, the authors indicate much more analysis could be done.

Delta Wing – A 65° delta wing was designed in early 1980 to study the effects of wing leading-edge bluntness on the onset and progression of leading-edge separation. The wing was designed for cryogenic conditions and had interchangeable leading edges with radii that were constant spanwise except very near the tip. The streamwise leading-edge radii, as normalized by the mean aerodynamic chord, were r/cbar = 0, 0.0005, 0.0015, and 0.0030. Here again, the design evolution for low observables was driving wing shapes toward minimal twist and camber and very small leading edge radii, so this basic delta wing geometry retained some relevance in the new context of low observability.

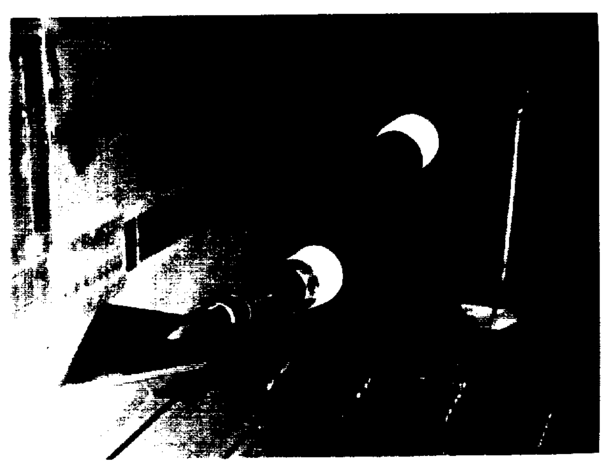


Fig. 19- Delta wing configuration.

These geometries were tested in the NTF in the summer of 1991. A photograph of the model is shown in Figure 19.The purpose of the test was to determine the effects of leading edge radius, Reynolds number and Mach number on leading-edge separation onset and progression for slender highly-swept wings. Delta wing force and pressure data were obtained from M=0.40 to 0.90 and Rn_c from 6 to 120 million (flight) at angles of attack from -2° to 28°.

The data from these tests were published without analysis[36-39] in order to expedite their availability. Preliminary CFD assessments for these data have also been published[40] and only showed limited success in capturing the pressure distributions for the blunt-edged vortex flows.

Some sample experimental results are presented below in Figure 20. Here the leading edge pressure distribution is shown for a low and a high Reynolds number condition at the same angle of attack to illustrate the Reynolds number effect in delaying the progression of separation up the leading edge. The low Reynolds number data show leading-edge separation at about 30% whereas at the higher Reynolds number this occurs at about 50%. In this particular case, the higher Reynolds number flow would have on the order of 80% more leading edge suction than its low Reynolds number counterpart.

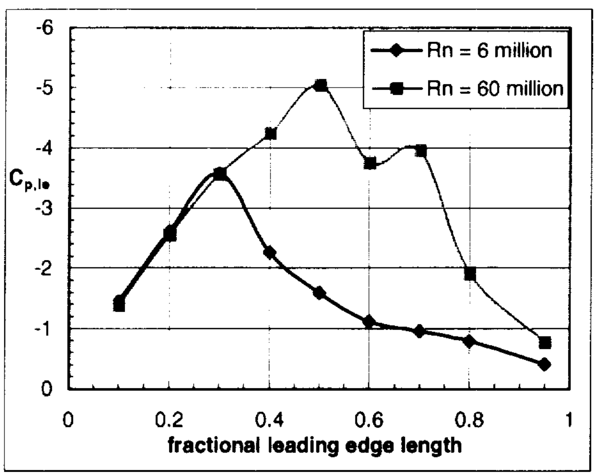


Fig. 20- Delta wing leading-edge pressures. Medium radius, $\alpha = 13°$, M=0.4.

A related view of this effect is presented in Figure 21. Here the pressure for a single tap half way down the leading edge is shown as a function of angle of attack for the same low and high Reynolds number conditions. Once again the Reynolds number effect on separation is very clearly seen, and differences persist over an angle of attack range from 10° to 20°. It is noted that the attached flow suction follows the expected $\sin^2\alpha$ theoretical trend shown by the dashed line. These results help to demonstrate that the experiment captured the desired Reynolds number effects on leading-edge separation. Further analysis of these effects is underway.

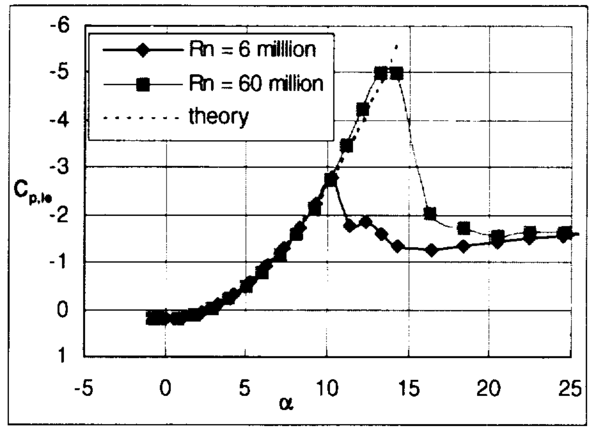


Fig. 21- Delta wing leading-edge pressure coefficient. Medium radius, 0.5 fractional leading-edge length, M=0.4

CONCLUDING REMARKS

A brief but complete summary of NTF tests of high-performance military configurations and related geometries has been presented. There were 12 such tests spanning a 15 year time period, much less testing for fighter aerodynamics than had originally been planned as a consequence of limited facility access and a variety of programmatic and resource issues. Even so, the tests did include full aircraft configurations, advanced concepts, research configurations, and basic research geometries. Ten of the twelve tests were cooperative ventures.

From an aerodynamic perspective a surprisingly robust suite of issues have been addressed with these tests. These include: wing design verification; flight certification data; ground-to-flight correlation data sets; cruise, maneuver and extreme-α aerodynamics; low Reynolds number data certification; wing control surface effects; empennage effects; high-lift aerodynamics; advanced forebody separation aerodynamics; and basic wing leading-edge separation effects.

Many of the data sets have only had limited analysis and in most cases the authors or principal researchers have recommended further inquiry into these data. This seems to be warranted as part of a process for selecting future research activities pertinent to high-performance military aerodynamics.

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