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Selected Experiments in Laminar Flow: An Annotated Bibliography

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Selected Experiments in Laminar Flow: An Annotated Bibliography

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CONTENTS

SUMMARY

Since the 1930s, there have been attempts to reduce drag on airplanes by delaying laminar to turbulent boundary layer transition. Experiments conducted during the 1940s, while successful in delaying transition, were discouraging because of the careful surface preparation necessary to meet roughness and waviness requirements. The resulting lull in research lasted nearly 30 years.

By the late 1970s, airframe construction techniques had advanced sufficiently that the high surface quality required for natural laminar flow (NLF) and laminar flow control (LFC) appeared possible on production aircraft. As a result, NLF and LFC research became widespread.

This report is an overview of that research. The experiments summarized herein were selected for their applicability to small transonic aircraft. Both flight and wind tunnel tests are included.

The description of each experiment is followed by corresponding references. Part One summarizes NLF experiments; Part Two deals with LFC and hybrid laminar flow control (HLFC) experiments.

INTRODUCTION

Growing concern over operating costs and the environmental effects of aircraft has led to an increasing interest in more efficient designs. For nearly 50 years it has been known that a substantial reduction in total aircraft drag could be obtained if the skin friction drag were reduced by delaying laminar to turbulent boundary layer transition.

With this goal in mind, a large number of experiments have been conducted. Many of these experiments successfully obtained extended runs of laminar flow. However, the difficulty of mass producing surfaces of quality equal to those used on experiments proved an insurmountable obstacle. Advances in composite construction and precision manufacturing during the last decade have given renewed hope that laminar flow aircraft may well be realistically achievable.

As a result, there has been increasing interest in applying natural laminar flow (NLF) and laminar flow control (LFC), as well as the more recent development, hybrid laminar flow control (HLFC), to all types of aircraft. One class of aircraft that has received particular attention is the light transonic jet: business jets and small airliners. This class of aircraft could benefit from NLF, LFC, or HLFC. Aircraft of this class are typified by cruise altitudes of 40,000–50,000 ft and cruise Mach numbers of 0.7–0.9.

This report is intended to be used as a reference for quickly identifying past laminar flow research (NLF, LFC, and HLFC) of interest. Experiments cited herein have been selected for their applicability to the above described class of aircraft. Included are wind tunnel and flight tests spanning a period from the first documented NLF/LFC research through what had been published at the time of writing.

The organization of this report is such that each section contains a description of the associated experiment followed by an annotated listing of corresponding references. A comprehensive bibliography at the end lists all of the referenced articles by author. A table summarizing the parameters of each experiment is also provided.

OVERVIEW

Section	Reynolds number ($\times 10^6$)	Mach number	Sweep, deg	NLF/LFC	Wind tunnel/ Flight
1.1	1 - 6	0.1 - 0.7	0 - 63	NLF	Both
1.2	1.4 - 10	0.1 - 0.4	–6 - 20	NLF	Both
1.3	25 - 30	0.80 - 0.85	9 - 26	NLF	Flight
1.4	5 - 34	0.6 - 0.825	15 - 35	NLF	Flight
1.5	12 - 30	0.35 - 0.7	13 - 23	NLF	Both
1.6.1	2.8 - 4.9	—	0	NLF	Flight
1.6.2	16 - 32	—	0	NLF	Flight
1.6.3	7 - 19	0.25 - 0.69	0	NLF	Flight
1.6.4	20	—	0	NLF	Flight
1.6.5	20	—	0	NLF	Flight
1.6.6	1.2 - 12	—	0, 30 - 40	NLF	Both
1.6.7	0.5 - 1.6	—	0	NLF	Wind tunnel
1.6.8	7 - 13	0.295 - 0.798	25	NLF	Flight
1.6.9	10	0.7	0	NLF	Wind tunnel
1.6.10	20	0.8	21	NLF	Flight
1.6.11	6.8 - 12.8	0.3 - 0.7	0	NLF	Wind tunnel
2.1	2 - 4	—	0	LFC	Wind tunnel
2.2	30	0.7	0	LFC	Flight
2.3	47	0.8	30	LFC	Flight
2.4	14	0.7	30.01	HLFC	Flight
2.5	10 - 22	0.82	23	LFC	Wind tunnel
2.6	25	0.2	30	LFC/HLFC	Wind tunnel

PART ONE: NATURAL LAMINAR FLOW

The first attempts to exploit the advantages of laminar flow utilized natural laminar flow (NLF). NLF relies on the shape of the wing, and the resulting pressure distribution to maintain laminar flow. The following are descriptions of some major NLF experiments.

1.1 "As-Produced" Aircraft

In the early 1980s, a series of experiments were performed on production samples of several general aviation aircraft at Langley Research Center by Bruce Holmes, Clifford Obara, Long Yip, and others.

The purpose of these tests was to gather data on the practicality of designing general aviation aircraft to exploit natural laminar flow on all airframe surfaces, not just wings. This included examining the effects of Reynolds number and Mach number on laminar to turbulent transition, observing the effects of sweep and attachment line contamination, observing propeller slipstream effects, determining the effects on transition of flight through rain and clouds, observing the effects on performance and stability when transition is forced near the leading edge, and investigating the nature of insect contamination.

Eight current production aircraft were flight tested. One was also tested in a wind tunnel. The aircraft were a Rutan VariEze, a Rutan Long-EZ, a Rutan Laser Biplane Racer, a Gates Learjet 28 Longhorn, a Cessna P210 Centurion, a Beech 24R Sierra, a Bellanca Skyrocket II, and a Beech T-34C. These aircraft were selected to represent a cross section of general aviation performance, mission, and construction methods, including both composite and aluminum airframes.

The flight tests were conducted over a wide range of conditions. Mach numbers from 0.1 to 0.7, chord Reynolds numbers from 1 million to 6 million, and sweep angles from 0 to 63 degrees were tested. The primary method of transition detection was the use of sublimation chemicals. In some cases, acoustic detection and hot film sensors were also used.

On each aircraft, both the upper and lower wing surfaces were examined. The other airframe surfaces examined included canards (VariEze, Long-EZ), winglets (Lear 28), propeller (Beech Sierra), wheel fairings (VariEze), and others.

In addition to the flight tests, the Rutan VariEze was tested in the Langley 30- by 60-Foot Wind Tunnel.

Holmes, Bruce J.: Natural Laminar Flow Hits Smoother Air. Aerospace America, July 1985.

Provides an introduction to NLF, its potential, and the results of the flight tests.

Holmes, Bruce J.; Coy, Paul F.; Yip, Long P.; Brown, Philip W.; and Obara, Clifford J.: Natural Laminar Flow Data from Full Scale Flight and Wind Tunnel Experiments. AIAA Conference Paper, 8th Annual General Aviation Technology Fest, Wichita, Kansas, November 13-14, 1981.

Results of NLF flight experiments are presented. Current airframe construction methods are shown to be adequate for NLF surfaces. Insect contamination and ice protection are stated as the most significant obstacles to widespread NLF use.

Holmes, B. J.; and Obara, C. J.: Observations and Implications of Natural Laminar Flow on Practical Airplane Surfaces. ICAS 82-5.1.1, 1982.

Contains summarized results of experiments for all eight aircraft. Includes comparison of surface waviness and roughness measurements to empirically determined allowable values.

Holmes, Bruce J.; Obara, Clifford J.; and Yip, Long P.: Natural Laminar Flow Experiments on Modern Airplane Surfaces. NASA TP-2256, 1984.

A report on all aspects of the experiment. Describes purpose, methods, and results. Includes photographs of sublimation results and airfoil coordinates for the aircraft wings.

Holmes, Bruce J.: Progress in Natural Laminar Flow Research. AIAA/NASA General Aviation Technology Conference Paper, Hampton, Virginia, July 10-12, 1984.

Flight test results are presented. Past NLF experiments are discussed. Recommendations for the direction of future NLF research are made.

Holmes, Bruce J.; Obara, Clifford J.; Martin, Glenn L.; and Domack, Christopher S.: Manufacturing Tolerances for Natural Laminar Flow Airframe Surfaces. SAE 850863, 1985.

Results of investigations on manufacturing tolerances for NLF surfaces and comparison with flight experiments. Fage's criteria are discussed. Recommendations are made for conservative manufacturing criteria for steps and gaps.

Obara, Clifford J.; and Holmes, Bruce J.: Flight-Measured Laminar Boundary-Layer Transition Phenomena Including Stability Theory Analysis. NASA TP-2417, 1985.

Report on experiment with Beech T-34C with an unswept NLF glove. Conducted at Mach numbers from 0.16 to 0.27 and Reynolds numbers from 4 million to 13 million. Includes results and airfoil coordinates.

Obara, Clifford J.; and Holmes, Bruce J.: Roughness and Waviness Requirements for Laminar Flow Surfaces. Langley Symposium on Aerodynamics, vol. 1, 1986, pp. 519-537.

Surface waviness and roughness requirements for laminar flow are discussed. Rcsearch on the effects of step shape on allowable height is discussed. Fage's and Carmichael's criteria for waviness are discussed.

1.2 Centurion

In 1987, a test was conducted at Langley Research Center by Daniel Murri, Frank Jordan, and others, in cooperation with Cessna Aircraft Company. The purpose of this test was to determine the flight characteristics of a general aviation aircraft designed for natural laminar flow. This involved wind tunnel tests of airfoil sections, full-scale wind tunnel tests of the aircraft, and flight tests.

For this test, the wings of a single-engine Cessna T210R Centurion were modified to the NASA NLF(1)-0414F airfoil shape by covering an aluminum surface with a polyester resin which was then sanded to shape. The two-dimensional airfoil was tested in the Langley Low Turbulence Pressure Tunnel at a chord Reynolds number of 10 million and Mach number of 0.4. Full-scale wind tunnel tests were conducted primarily to investigate low-speed and stall/spin characteristics. These were conducted at chord Reynolds numbers of 1.4 million to 2.4 million. The angle of attack varied from –6 to 40 degrees, and sideslip angles from –6 to 20 degrees were tested.

To detect laminar to turbulent transition, hot film gauges and sublimation chemicals were used in the flight tests. Tufts were attached to the upper wing surface during the full-scale wind tunnel tests for flow visualization. The airfoil-alone tests used thin-film transition gages.

The airfoil was designed to maintain laminar flow over the first 70% chord on both upper and lower surfaces. In both wind tunnel and flight tests, the transition fronts were observed at approximately 70% chord. Flight tests conducted to explore certification issues revealed that forcing transition near the leading edge resulted in increased drag, but did not detrimentally affect stability or handling characteristics.

It was reported by *Aviation Week and Space Technology* (Oct. 1, 1990, pg. 49) that these tests convinced Cessna Aircraft Company to pursue natural laminar flow technology for their Model 525 CitationJet.

Berry, Scott A.; Dagenhart, J. Ray; Viken, Jeffrey K.; and Yeaton, Robert B.: Boundary-Layer Stability Analysis of NLF and LFC Experimental Data at Subsonic and Transonic Speeds. SAE 871859, 1988.

Presents the results of a boundary layer stability analysis of wind tunnel and flight tests. Additionally, data from a wind tunnel test on a swept LFC airfoil are considered.

Doty, Wayne A.: Flight Test Investigation of Certification Issues Pertaining to General-Aviation-Type Aircraft with Natural Laminar Flow. NASA CR-181967, 1990.

Flight test results are presented. An emphasis is placed on differences in aircraft behavior with natural transition and transition fixed near the leading edge. Increased drag was observed for the fixed transition case, however handling qualities remained the same.

McGhee, Robert J.; Viken, Jeffrey K.; Pfenninger, Werner; Beasley, William D.; and Harvey, William D.: Experimental Results for a Flapped Natural-Laminar-Flow Airfoil with High Lift/Drag Ratio. NASA TM-85788, 1984.

Contains results and details of a wind tunnel test of the airfoil used on the Centurion. The tests were conducted in the Langley Low Turbulence Pressure Tunnel.

Murri, Daniel G.; and Jordan, Frank L., Jr.: Wind-Tunnel Investigation of a Full-Scale General Aviation Airplane Equipped With an Advanced Natural Laminar Flow Wing. NASA TP-2772, 1987.

Reports results of wind tunnel tests including low speed stability, cruise performance, and stall behavior. Explains experimental objectives and procedures.

Murri, Daniel G.; Jordan, Frank L., Jr.; Nelson, Randy; and Davis, Patrick J.: Wind-Tunnel Investigation of a General Aviation Airplane Equipped with a High Aspect-Ratio, Natural-Laminar-Flow Wing. SAE 871019, 1988.

Presents an evaluation of performance, stability, and control characteristics observed in the wind tunnel tests. Discuses test procedures and measurement methods.

Viken, Jeffrey K.; Pfenninger, Werner; and McGhee, Robert J.: Advanced Natural Laminar Flow Airfoil with High Lift to Drag Ratio. NASA Langley Symposium on Aerodynamics, vol. 1, 1986, pp. 401-414.

Contains results and details of a wind tunnel test of the airfoil used on the Centurion. The tests were conducted in the Langley Low Turbulence Pressure Tunnel.

1.3 F-111 TACT

In 1981, an experiment was conducted as part of the Aircraft Energy Efficiency Program by Lawrence Montoya, Louis Steers, David Christopher, and Bianca Trujillo of the Lewis Research and Dryden Flight Research Centers. The wing of an F-111, designated the Transonic Aircraft Technology (TACT) aircraft, was fitted with a laminar flow glove for the purpose of evaluating the extent of natural laminar flow that could be consistently obtained under real flight conditions with varying sweep angles. Before flight testing, a 1/24-scale model was tested in the Langley 8-Foot Transonic Pressure Tunnel.

The glove consisted of a supercritical airfoil shape designed to provide a favorable pressure gradient to 65% chord of the upper surface and 50% of the lower. The 1.829 m span glove was instrumented with pressure orifices and boundary layer rakes.

A total of 19 flights were made at Mach numbers from 0.80 to 0.85, and Reynolds numbers of 25 million to 30 million. During these tests, the leading edge sweep was varied from 9 to 26 degrees. Oil flow photographs were used to augment the boundary layer measurements and pressure distributions obtained.

The observed transition fronts varied with sweep angle. On the upper surface, they appeared from 0 to 56% chord, and on the lower surface, 0 to 51% chord.

Boeing Commercial Airplane Company, Preliminary Design Department: F-111 Natural Laminar Flow Glove Flight Test Data Analysis and Boundary Layer Stability Analysis. NASA CR-166051, 1984.

In-depth results of the F-111 NLF glove flight test data analysis and boundary layer analysis are presented.

Meyer, Robert R., Jr.; and Jennett, Lisa A.: In-Flight Surface Oil Flow Photographs With Comparisons to Pressure Distribution and Boundary-Layer Data. NASA TP-2395, 1985.

Oil flow photographs are interpreted and compared with boundary layer analysis. Use of oil flow photographs for flight test analysis is discussed. Includes color oil flow photos of flight tests.

Montoya, Lawrence C.; Steers, Louis L.; Christopher, David; and Trujillo, Bianca: F-111 TACT Natural Laminar Flow Glove Flight Results. NASA CR-2208, 1981.

Test methods and procedures are discussed. Preliminary pressure distribution and boundary layer analysis of the flight data are presented.

Runyan, L. James; and Steers, Louis L.: Boundary Layer Stability Analysis of a Natural Laminar Flow Glove on the F-111 TACT Airplane. Viscous Flow Drag Reduction, Gary R. Hough, ed., AIAA, 1979, pp. 17-32.

A summary of boundary layer analysis on the F-111 wing glove. Effects of wing sweep, Reynolds number, and compressibility on boundary layer stability and transition are discussed.

1.4 F-14 VSTFE

In 1989, an experiment was conducted at the Ames-Dryden Flight Research Facility by Bianca Trujillo Anderson and Robert Meyer. Known as the Variable-Sweep Transition Flight Experiment (VSTFE), its purpose was to observe the effects of wing sweep on boundary layer transition for typical transport aircraft conditions.

An F-14A equipped with two different, nearly full span, partial chord wing gloves was used. One glove preserved the original F-14 wing contour, while the other was specially designed to provide pressure gradients favorable to natural laminar flow at Mach 0.7 and 20 degrees of leading edge sweep.

In addition to built-in pressure orifices, hot film sensors and boundary layer pitot rakes were used to detect transition location.

The tests were conducted at altitudes of 10,000 to 35,000 ft and Mach numbers between 0.600 and 0.825. The chord Reynolds numbers varied from 5 million to 34 million. The leading edge sweep angle was varied from 15 to 35 degrees, in 5 degree increments.

Location of the transition front was found to be dependent on wing sweep. At high sweep angles, transition moved forward. Over the range of conditions tested, transition location was highly dependent on sweep angle, occurring over a range of 4% to 50% chord from the leading edge.

Anderson, Bianca Trujillo; and Meyer, Robert R., Jr.: Effects of Wing Sweep on Boundary-Layer Transition for a Smooth F-14A Wing at Mach Numbers from 0.700 to 0.825. NASA TM-101712, 1990.

Discusses experiment objectives and procedures. Presents results for the smooth F-14 wing. Includes microfiche supplement giving pressure coefficients, boundary layer velocity profile data, and boundary layer transition locations.

Anderson, Bianca Trujillo; and Meyer, Robert R., Jr.: Effects of Wing Sweep on In-Flight Boundary-Layer Transition for a Laminar Flow Wing at Mach Numbers from 0.60 to 0.79. NASA TM-101701, 1990.

Discusses experiment objectives and procedures. Presents results for the F-14 with an NLF glove. Indicates that a substantial amount of laminar flow was maintained. Includes microfiche supplement containing pressure coefficients, boundary layer velocity profile data, and boundary layer transition locations.

Meyer, Robert R.; Trujillo, Bianca M.; and Bartlett, Dennis W.: F-14 VSTFE and Results of the Cleanup Flight Test Program. Research in Natural Laminar Flow and Laminar Flow Control, NASA CP-2487, 1987, pp. 819-844.

Describes the background and history of the VSTFE program and presents preliminary results of the cleanup of the F-14 wing.

Rozendaal, R. A.: Variable-Sweep Transition Flight Experiment (VSTFE) —Stability Code Development and Clean-Up Glove Data Analysis. Research in Natural Laminar Flow and Laminar Flow Control, NASA CP-2487, 1987, pp. 845-860.

Describes how linear stability theory was used to analyze data from VSTFE. Development and application of the unified stability system are described. Results from the cleanup of the F-14 wing are included.

1.5 Airbus

In 1986, the German Ministry of Research and Technology initiated a transonic laminar flow program for the purpose of exploring the applications of natural laminar flow (NLF) to transport aircraft. This three year program was conducted jointly by Deutsche Forschungsanstalt für Luft- und Raumfahrt (DLR) and Deutsche Airbus GmbH. The program consisted of both wind tunnel and flight tests, and its goal was to establish a reliable data base for transition prediction.

The flight tests were conducted using a VFW 614 40-seat jet aircraft with an NLF glove on one-third of the right wing. Mach number varied from 0.35 to 0.70 and Reynolds number from 12 million to 30 million. Leading edge sweep for the aircraft was 18 degrees and was varied during the test, by sideslipping, from 13 to 23 degrees. Transition measurements were made using hot film sensors and infrared imaging. The latter technique was considered valuable by the experimenters.

Wind tunnel tests were conducted using a half-scale model of the wing. These were conducted in two facilities, the Deutsche Niederlandischer Wind Kanal's 8 × 6 m test section and the French SIMA 8 m transonic tunnel. Low speed testing was done in each tunnel (Mach = 0.27) and transonic testing, from Mach = 0.47 to 0.70, in the SIMA facility. Reynolds numbers were approximately 9 million in the DNW and as high as 18 million at SIMA. Transition measurements were made using pitot wake rakes, hot film sensors, piezoelectric film, and infrared imaging.

Measurements over a variety of conditions in the wind tunnels showed transition occurring as far aft as 55% chord. In flight tests, transition consistently occurred at approximately 40% chord. As of January 1992, detailed results had not been published.

Henke, R.; Munch, F. X.; and Quast, A.: Natural Laminar Flow: A Wind Tunnel Test Campaign and Comparison with Flight Test Data. AIAA Paper 90-3045-CP, 1990.

Results of the wind tunnel tests are presented. Procedures, objectives and measurement methods are described. Methods of comparing wind tunnel results to flight test results are discussed.

Horstmann, K. H.; Redeker, G.; Quast, A.; Dressler, U.; and Bieler, H.: Flight Tests with a Natural Laminar Flow Glove on a Transport Aircraft. AIAA Paper 90-3044-CP, 1990.

Procedures and results of flight tests are discussed. Test methods are explained.

Nitsche, W.; and Szodruch, J.: Concepts and Results for Laminar Flow Research in Wind Tunnel and Flight Experiments. ICAS 90-6.1.4, 1990.

Procedures and measurement methods for laminar flow testing are discussed. The flight and wind tunnel tests are used as examples.

Redeker, G.; Horstmann, K. H.; Koster, H.; Thiede, P.; and Szodruch, J.: Design of a Natural Laminar Flow Glove for a Transport Aircraft. AIAA Paper 90-3043-CP, 1990.

The process by which the wing glove for this experiment was designed is discussed. The stability behavior of the glove is analyzed in detail.

Redeker, G.; Horstmann, K. H.; Koster, H.; and Quast A.: Investigations on High Reynolds Number Laminar Flow Airfoils. Journal of Aircraft, vol. 25, no. 7, July 1988.

Airfoil design and transition prediction are discussed. Two- and three-dimensional stability theory and its usefulness are also presented.

1.6 Other Tests

The following is a chronological presentation of some additional NLF tests. Though these tests were smaller in scope than those presented in preceding sections, they show important steps in the development of NLF technology.

1.6.1 Klem L56 Va– In 1934, a flight experiment was conducted by J. Stuper using a Klem L56 Va low-wing monoplane. The purpose of the experiment was to investigate the nature of the wing boundary layer and validate Gruschwitz's formulas for boundary layer thickness and profile form drag.

Stuper, J.: Investigation of Boundary Layers on an Airplane Wing in Free Flight. NACA TM-751, 1934.

1.6.2 B-18 Glove– In 1941, a 17 ft chord NACA 35-215 glove was placed on the wing of a Douglas B-18. Flight tests were conducted at Reynolds numbers from 16 million to 32 million to determine laminar to turbulent boundary layer transition locations. Transition was at approximately 40% chord for most conditions, but only after extensive surface preparation.

Wetmore, J. W.; Zalovick, J. A.; and Platt, Robert C.: A Flight Investigation of the Boundary-Layer Characteristics and Profile Drag of the NACA 35-215 Laminar-Flow Airfoil at High Reynolds numbers. NACA WR L-532, 1941.

1.6.3 P-47– A flight experiment using filled and sanded wing sections of a Republic P-47D aircraft was conducted in 1945. The sections tested had a chord measurement of approximately 7 feet. The tests were conducted at Reynolds numbers from 7 million to 19 million, and Mach numbers from 0.25 to 0.69. Laminar transition fronts were detected between 15% and 20% chord.

Zalovick, John A.: Flight Investigation of Boundary-Layer and Profile Drag Characteristics of Smooth Wing Sections of a P-47D Airplane. NACA ACR L5H11a, 1945.

Zalovick, John A.; and Skoog, R. B.: Flight Investigation of Boundary-Layer Transition and Profile Drag on an Experimental Low-Drag Wing Installed on a Fighter-Type Airplane. NACA WR L-94, 1945.

1.6.4 Hurricane II– A Hawker Hurricane II equipped with specially designed wings was flight tested at Reynolds numbers as high as 20 million. It was found that laminar to turbulent transition could occur under these conditions at 50% to 60% chord once the wing had been smoothed sufficiently.

Plascott, R. H.; Higton, D. J.; Smith, F.; and Bramwell, A. R.: Flight Tests on Hurricane II, Z.3687 Fitted With Special Wings of 'Low Drag' Design. British R&M 2546, 1946.

Plascott, R. H.: Profile Drag Measurements on Hurricane II Z.3687 Fitted with Low-Drag Section Wings. RAE Report No. Aero 2153, 1946.

1.6.5 King Cobra– In 1945, an experiment was conducted in which the production wings of a Bell King Cobra fighter aircraft were filled and sanded to reduce waviness and gaps. The aircraft was then flight tested 50 times for the purpose of determining section drag coefficients and boundary layer state. The aircraft was found to have significant runs of laminar flow, even at Reynolds numbers approaching 20 million.

Gray, W. E.; and Fullam, P. W. J.: Comparison of Flight and Tunnel Measurements of Transition on a Highly Finished Wing (King Cobra). RAE Report Aero 2383, 1945.

Smith, F.; and Higton, D.: Flight Tests on King Cobra FZ.440 to Investigate the Practical Requirements for the Achievement of Low Profile Drag Coefficients on a 'Low Drag' Aerofoil. ARC Report, R&M 2375, 1950.

1.6.6 Phoenix Sailplane– In 1979, the Boeing Commercial Airplane Company used a modified linear stability code to analyze two cases where boundary layer characteristics had been measured: a flight tested Phoenix sailplane and a swept wing, utilizing a different airfoil shape, in a low turbulence wind tunnel.

Runyan, L. J.; and George-Falvy, D.: Amplification Factors at Transition on an Unswept Wing in Free Flight and on a Swept Wing in a Wind Tunnel. AIAA Paper 79-0267, 1979.

1.6.7 Scale Light Plane– A one-fifth scale model of a single-engine general aviation aircraft equipped with a 15% thick natural laminar flow airfoil was tested in the Texas A&M University 2.13 m x 3.05 m low-speed wind tunnel. The airfoil was designed for laminar flow to 40% chord. Testing of stall behavior was done both with natural transition and with transition fixed near the leading edge.

Ostowari, C.; and Naik, D. A.: An Experimental Study of a General Aviation Single-Engine Aircraft Utilizing a Natural Laminar Flow Wing. SAE 850861, 1985.

1.6.8 Citation III– A smoothed section of the wing of a Cessna model 650 Citation III was flight tested to measure the extent of laminar flow on a 25 degree swept wing business jet. Tests were conducted at Mach numbers from 0.295 to 0.798. Hot-film anemometry and sublimation chemicals were used to detect the location of transition fronts.

Rozendaal, R. A.: Natural Laminar Flow Flight Experiments on a Swept-Wing Business Jet—Boundary-Layer Stability Analyses. NASA CR-3975, 1985.

Wentz, W. H., Jr.; Ahmed, A.; and Nyenhuis, R.: Further Results of Natural Laminar Flow Flight Test Experiments. SAE 850862, 1985.

Wentz, W. H., Jr.; Nyenhuis, R.; and Ahmed, A.: Natural Laminar Flow Flight Experiments on a Swept-Wing Business Jet. AIAA 2nd Applied Aerodynamics Conference, Seattle, Washington, August 21-23, 1984.

1.6.9 HSNLF(1)-0213– A 13% thick natural laminar flow airfoil was designed for use on a light transonic business jet by the Applied Aerodynamics Group of the National Transonic Facility Aerodynamics Branch at Langley Research Center. The airfoil, based on the low-speed NLF(1)-0414F airfoil, was tested in the Langley 6- by 28-Inch Transonic Tunnel and in the Langley Low Turbulence Pressure Tunnel. The airfoil was designed to operate at Mach 0.7 with a lift coefficient of 0.2 and have 50% chord runs of laminar flow on the upper surface and 70% on the lower.

Campbell, R. L.; Waggoner, E. G.; and Phillips, P. S.: Design of a Natural Laminar Flow Wing for a Transonic Corporate Transport. AIAA Paper 86-0314, 1986.

Sewall, William G.; McGhee, Robert J.; Viken, Jeffery K.; Waggoner, Edgar G.; Walker, Betty S.; and Millard, Betty F.: Wind Tunnel Results for a High-Speed, Natural Laminar-Flow Airfoil Designed for General Aviation Aircraft. NASA TM-87602, 1985.

1.6.10 Boeing 757– A natural laminar flow wing glove was designed and mounted on a Boeing 757 transport aircraft. Located just outboard of the right engine nacelle, it was used to investigate the effect of engine noise on laminar flow. The glove had a span of 10 feet and a chord of 6 feet before fairing smoothly into the existing wing. The leading edge sweep of the glove was 21 degrees, less than that of the original wing. Instrumentation used consisted of microphones, pressure belts, and hot film gages. Measurements were taken over a wide range of engine settings. The results of these tests indicated that engine noise has a very small effect on boundary layer transition.

Boeing Commercial Airplane Company: Flight Survey of the 757 Wing Noise Field and Its Effects on Laminar Boundary Layer Transition, Volume I—Program Description and Data Analysis. NASA CR-178216, March 1987.

Boeing Commercial Airplane Company: Flight Survey of the 757 Wing Noise Field and Its Effects on Laminar Boundary Layer Transition, Volume II—Data Compilation. NASA CR-178217, March 1987.

Boeing Commercial Airplane Company: Flight Survey of the 757 Wing Noise Field and Its Effects on Laminar Boundary Layer Transition, Volume III—Extended Data Analysis. NASA CR-178419, March 1988.

Runyan, L. J.; Bielak, G. W.; Behbehani, R.; Chen, A. W.; and Rozendaal, R. A.: 757 NLF Glove Flight Test Results. NASA CP-2487, March 1987.

1.6.11 De Havilland– Four natural laminar flow airfoils of different thicknesses were developed by Boeing Canada (de Havilland) Aircraft and the National Aeronautical Establishment of Canada. These airfoils were then tested in NAE's High Reynolds Number Trisonic Facility and analyzed using the GRUMFOIL code. The results were compared and found to be only partly in agreement.

Khalid, M.; Jones, D. J.; and Eggleston, B.: Wind Tunnel Results and Numerical Computations for the NAE/de Havilland Series of Natural Laminar Flow Airfoils. CASI 1st Canadian Symposium on Aerodynamics, Ottowa, Canada, December 4-5, 1989, pp. 2-1 to 2-17.

Khalid, M.; and Jones, D. J.: A Summary of Transonic Natural Laminar Flow Airfoil Development at NAE. NAE-AN-65, 1990.

PART TWO: LAMINAR FLOW CONTROL

The following are descriptions of some laminar flow control (LFC) and hybrid laminar flow control (HLFC) experiments. The described experiments are arranged in chronological order since each experiment built on the results of the previous experiments.

2.1 An Early LFC Wind Tunnel Experiment

In the mid-1940s, an LFC wind tunnel experiment was conducted by Werner Pfenninger. At this time the idea of keeping boundary layers laminar by the use of suction was very new. This experiment included numerous phases, including the testing of a 2 meter chord airfoil equipped with eight suction slots in a wind tunnel. The tests were conducted at Reynolds numbers of 2 million to 4 million with various slot sizes and geometries. The results were encouraging.

Pfenninger, Werner: Investigations on Reductions of Friction on Wings, in Particular by Means of Boundary Layer Suction. NACA TM-1181, August 1947.

2.2 F-94A

The first major laminar flow control flight experiment was conducted from 1952 to 1955 using an F-94A aircraft fitted with unswept partial span wing gloves. The tests were conducted by Northrop under an Air Force contract. Three suction gloves were tried, differing only in the number of slots employed.

The first tests used a full chord, 49 inch span LFC glove with 12 suction slots on the upper surface. The spanwise slots were placed between 41% and 94% chord. Moving aft, each slot became successively shorter in the spanwise direction. The initial slot measured 32.5 inches in length, the last only 9 inches. It was believed that suction slots would be more effective than individual holes, which had been found to act as three-dimensional disturbances causing premature transition in wind tunnel tests. Great pains were taken to ensure a nearly wave-free surface. Measured wave amplitudes over 1 inch lengths were less than 0.001 inch. Similar care was taken to ensure that steps formed by the suction slots would not interfere with the boundary layer. The second and third suction gloves differed from the first only in the number of slots. The second glove consisted of 69 slots arranged in the same area as the 12 slot glove. The third glove had the same arrangement with 81 slots.

The purpose of the tests was to achieve full chord runs of laminar flow in flight. Flights were conducted between 6,000 and 30,000 ft at Mach numbers up to 0.7. Chord Reynolds numbers were as high as 30 million.

Full-chord laminar flow was achieved with each of the three gloves. However, it was found that the more slots on the glove, the lower the total drag. Much of the difficulty in achieving laminar runs was a result of adjusting the suction pumps correctly.

Carmichael, B. H.; Whites, R. C.; and Wisma, R. E.: Low Drag Boundary Layer Suction Experiments in Flight on the Wing Glove of an F94-A Airplane. Northrop Aircraft, Inc., Report No. BLC-102, August 1957.

Provides an overview of all phases of the F-94 program. Briefly describes experiment purposes and results.

Carmichael, B. H.; Whites, R. C.; and Pfenninger, W.: Low Drag Boundary Layer Suction Experiments in Flight on the Wing Glove of an F94A Airplane—Phase III – Laminar Suction Airfoil Tolerances. Northrop Aircraft, Inc., Report No. BLC-101, September 1957.

Presents results of 81 slot glove test. Additionally, experiments were conducted on suction requirements during various flight phases.

Groth, E. E.; Carmichael, B. H.; Whites, P. C.; and Pfenninger, W.: Low Drag Boundary Layer Suction Experiments in Flight on the Wing Glove of an F94-A Airplane—Phase II – Suction Through 69 Slots. Northrop Aircraft, Inc., Report No. BLC-94, February 1957.

Modification of the glove from its 12 slot version to the 69 slot model is discussed. Subsequent flight tests and results are also included.

Pfenninger, W.; Groth, E. E.; Carmichael, B. H.; and Whites, R. C.: Low Drag Boundary Layer Suction Experiments in Flight on the Wing Glove of an F94-A Airplane—Phase I – Suction Through 12 Slots. Northrop Aircraft, Inc., Report No. BLC-77, April 1955.

Construction of the initial glove is discussed. Procedures and results of flight tests with the 12 slot glove are presented. Wind tunnel tests used in design of the glove are also discussed.

2.3 X-21

In the early 1960s, an LFC flight test was conducted for the U.S. Air Force by Northrop Corporation. The X-21 was the first LFC flight test vehicle to employ swept wings. Suction was provided through spanwise slots distributed from leading to trailing edge of the wing. Flight tests were conducted at speeds up to Mach 0.8 and altitudes as high as 40,000 ft. The results from these tests were generally encouraging.

The X-21 was an extensively modified B-66. The modification included replacing the wing-mounted jet engines with tail mounted ones and replacing the wing with an entirely new design. The new wing was designed specifically for LFC. Eighty percent of the wetted area was covered by suction slots. These slots were connected through internal ducts to suction pumps, one on each side, mounted in nacelles beneath the wing. The wing itself was approximately 12.5% thick at the root, tapering to 10% near the tip. Leading edge sweep was 30 degrees. The wing was assembled with large skin panels. The gaps and steps between these panels were then filled with an epoxy filler. The design of this wing was based on tests of a 30 degree swept LFC wing in the 12-ft pressure tunnel at NASA Ames Research Center.

Testing was conducted over a wide range of flight conditions. Chord Reynolds numbers were as high as 47 million. Cruise speeds as high as Mach 0.8 at 40,000 ft were also tested.

Despite early problems with attachment line contamination, the results of these tests were generally encouraging. Full chord laminar flow was attainable repeatedly under most flight conditions. Stability and control of the aircraft was satisfactory with both laminar and turbulent boundary layers.

Fowell, L. R.; and Antonatos, P. P.: Laminar Flow Flight Test Results on the X-21A. AGARDograph 97, Part 2, May 1965.

Presents the results of initial flights. Discusses the stability of the boundary layer in various flight conditions. Results are presented for flights up to 40,000 ft and chord Reynolds numbers up to 20 million.

Kosin, Ruediger E.: Laminar Flow Control by Suction as Applied to the X-21A Airplane. Journal of Aircraft, pp. 384-390, September-October 1965.

An overview of the X-21 program is given. Results of flight tests are presented and the wind tunnel tests used to design the X-21 systems are also discussed.

Pfenninger, W.: Flow Phenomena at the Leading Edge of Swept Wings. AGARDograph 97, Part 1, May 1965.

The attachment line contamination discovered in the X-21 flight tests is discussed. Methods for controlling this are presented.

Quick, J. W.: Laminar Flow Control Demonstration Program Final Report—LFC Manufacturing Techniques. Northrop Aircraft Company, Report No. NOR-61-142, March 1964.

Provides a detailed description of the modification of the aircraft for flight testing. Also described are methods of manufacture designed to meet surface quality and other requirements imposed on laminar flow aircraft.

Stark, W. W.: LFC Summary Flight Test Report. Northrop Aircraft Company, Report No. NOR-61-134, April 1964.

Provides flight test data and outlines analysis procedure.

Whites, R. C.; Sudderth, R. W.; and Wheldon, W. G.: Laminar Flow Control on the X-21. Astronautics and Aeronautics, July 1966.

Describes the aircraft and test procedures. Outlines the goals of the tests and discusses instrumentation. Some results are shown.

X-21A Engineering Section, Northrop Corporation: Final Report—LFC Aircraft Design Data Laminar Flow Control Demonstration Program. Northrop Corp., Report No. NOR-67-136, June 1967.

Complete report describing all aspects of X-21 program. Includes details of external and internal aerodynamics, boundary layer theory, propulsion, LFC design criteria, aircraft performance, and structural design and analysis. Also summarizes state of the art in LFC aircraft design.

2.4 Jetstar LEFT

During the 1980s, the leading edge flight test program (LEFT) was conducted by Langley Research Center to establish a data base on the use of hybrid laminar flow control (HLFC) in real operating environments. A Lockheed Jetstar four-engine business jet was equipped with two partial span leading edge wing gloves of different designs. The aircraft was then flown extensively under a wide variety of atmospheric and environmental conditions. Of major interest was the durability of LFC wings in the real world. Susceptibility to damage and insect contamination and de-icing capabilities were studied.

The glove on the right wing was manufactured by Douglas Aircraft Company. Using an electron beam perforated titanium surface, the glove provided suction on the upper surface only, from the leading edge to 13% chord. A retractable flap hinged on the lower surface, similar to a Krueger-type flap, was employed as an insect shield for use during takeoff and landing. Nozzles on the underside of the flap could spray the leading edge with a propylene glycol-methyl ether solution to remove insect debris and ice.

The glove on the left wing was manufactured by the Lockheed Georgia Company. Using spanwise slots, it maintained suction over both the upper and lower surfaces of the leading edge region. De-icing and insect protection were achieved by using suction slots at the leading edge to exude a propylene glycol-methyl ether solution when necessary.

Both gloves performed well throughout the test. During the four year program, there was no appreciable degradation in performance. The anti-insect and de-icing systems were found to be essential.

Douglas Aircraft Company: Laminar Flow Control Leading Edge Glove Flight Test Article Development. NASA CR-172137, 1984.

Provides a detailed discussion of the design and fabrication of the Douglas LEFT glove.

Etchberger, F. R.: LFC Leading Edge Glove Flight Test—Aircraft Modification Design, Test Article Development, and System Integration. NASA CR-172136, 1983.

Presents a detailed discussion of the design and fabrication of the Lockeed LEFT glove. Also discusses the modifications to the Jetstar aircraft required to incorporate the leading edge gloves.

Maddalon, Dal V.; and Braslow, Albert L.: Simulated-Airline-Service Flight Tests of Laminar-Flow Control With Perforated Surface Suction System. NASA TP-2966, 1990.

Discusses effectiveness and practicality of suction systems in real world operating environment. Performance of the leading edge slat/bug shield is also discussed.

Wagner, Richard D.; and Fischer, Michael C.: Fresh Attack on Laminar Flow. Aerospace America, March 1984, pp. 72-76.

Contains an overview of Jetstar experiment, construction of wing gloves and application of LFC to commercial aircraft.

2.5 Langley 8-Foot Wind Tunnel LFC

In the late 1980s, a laminar flow control (LFC) wind tunnel experiment was conducted in the 8-Foot Transonic Pressure Tunnel at Langley Research Center. The test used an 8-ft span, 23 degree leading edge sweep, supercritical wing with an SCLFC(1)-0513F airfoil. For the test, the wind tunnel was extensively modified. The tunnel walls were faired to simulate flow conditions on an infinite swept wing. Further, honeycomb screens were installed in the tunnel in an effort to reduce the free stream turbulence. The airfoil was designed for a free stream Mach number of 0.82 and was tested at Reynolds numbers from 10 million to 22 million.

The purposes of the test were to determine the practicality of using laminar flow control on swept, supercritical airfoils and to validate transition prediction techniques. Suction through span-wise slots and suction through a porous surface were both tested. Full-chord laminar flow was achieved at Mach numbers from 0.4 to 0.82 and Reynolds numbers as high as 22 million.

Berry, Scott; Dagenhart, J. R.; Brooks, C. W.; and Harris, C. D.: Boundary-Layer Stability Analysis of LaRC 8-Foot LFC Experimental Data. NASA CP-2487, 1987, pp. 471-489.

Compares data obtained from early experiments with slotted suction wing

Bobbitt, P.; Ferris, J.; Harvey, W.; and Goradia, S. H.: Results for the Hybrid Laminar Flow Control Experiment Conducted in the NASA Langley 8-ft Transonic Pressure Tunnel on a 7-ft Chord Model. NASA TM-107582, 1992.

Brooks, C. W., Jr.; and Harris, C. D.: Results of LFC Experiment on Slotted Swept Supercritical Airfoil in Langley's 8-Foot Transonic Pressure Tunnel. NASA CP-2487, 1987, pp. 453-469.

Provides a description of experiment and tunnel modifications. Discusses results of early slotted suction experiments and makes comparisons with turbulent airfoils as well as earlier LFC tests.

Harvey, W. D.; and Pride, J. D.: The NASA Langley Laminar Flow Control Airfoil Experiment. AIAA Paper 82-0567, March 1982.

Describes design and construction of airfoil. Discusses prediction methods intended to be validated by the experiment. Presents plan for the experiment.

2.6 Boeing Wind Tunnel

A laminar flow control test was conducted in the Boeing Aircraft Company's 5 × 8 ft low-speed wind tunnel. This experiment was designed to test laminar flow control on a nearly full-scale, swept, transport aircraft wing. Two different types of suction were tested.

The model installed in the wind tunnel was designed to simulate an infinite swept wing at typical transonic cruise conditions. The airfoil shape used was thus designed to have the same pressure distribution in the tunnel environment as on an actual wing at cruise conditions. As a result the airfoil shape is very different from an actual aircraft. In order to simulate an infinite swept wing, the wing is of constant cross section with a 30 degree leading edge sweep. A fairing was used on the tunnel walls to reduce their influence.

Initially, suction was provided through spanwise slots over the first 30% chord of the wing. In the second phase, suction was through laser-drilled holes in a titanium leading edge. In these tests, the suction region covered only the first 20% chord of the wing. The first tests (slotted suction) were called LFC tests and the later (hole suction) tests were called HLFC.

George-Falvy, D.: Laminar Flow Test Installation in the Boeing Research Wind Tunnel. AIAA Paper 90-1425, June 1990.

Provides description of experiment and setup. Focus is on the first phase where suction is through spanwise slots.

Parikh, P. G.; Lund, D. W.; George-Falvy, D.; and Nagel, A. L.: Hybrid Laminar Flow Control Tests in the Boeing Research Wind Tunnel. SAE 901978, October 1990.

Provides description of experiment and setup. Focus is on the second phase where suction was through holes in laser-drilled titanium.

BIBLIOGRAPHY

Anderson, Bianca Trujillo; and Meyer, Robert R., Jr.: Effects of Wing Sweep on Boundary-Layer Transition for a Smooth F-14A Wing at Mach Numbers From 0.700 to 0.825. NASA TM-101712, 1990. [Referenced in section 1.4]

Anderson, Bianca Trujillo; and Meyer, Robert R., Jr.: Effects of Wing Sweep on In-Flight Boundary-Layer Transition for a Laminar Flow Wing at Mach Numbers From 0.60 to 0.79. NASA TM-101701, 1990. [Referenced in section 1.4]

Berry, Scott; Dagenhart, J. R.; Brooks, C. W.; and Harris, C. D.: Boundary-Layer Stability Analysis of LaRC 8-Foot LFC Experimental Data. NASA CP-2487, 1987, pp. 471-489. [Referenced in section 2.5]

Berry, Scott A.; Dagenhart, J. Ray; Viken, Jeffrey K.; and Yeaton, Robert B.: Boundary-Layer Stability Analysis of NLF and LFC Experimental Data at Subsonic and Transonic Speeds. SAE 871859, 1988. [Referenced in section 1.2]

Bobbitt, P.; Ferris, J.; Harvey, W.; and Goradia, S. H.: Results for the Hybrid Laminar Flow Control Experiment Conducted in the NASA Langley 8-ft Transonic Pressure Tunnel on a 7-ft Chord Model. NASA TM-107582, 1992. [Referenced in section 2.5]

Boeing Commercial Airplane Company, Preliminary Design Department: F-111 Natural Laminar Flow Glove Flight Test Data Analysis and Boundary-Layer Stability Analysis. (NASA Contract NAS1-15325) NASA CR-166051, 1984. [Referenced in section 1.3]

Boeing Commercial Airplane Company: Flight Survey of the 757 Wing Noise Field and Its Effects on Laminar Boundary Layer Transition, Volume I—Program Description and Data Analysis. NASA CR-178216, March 1987. [Referenced in section 1.6.10]

Boeing Commercial Airplane Company: Flight Survey of the 757 Wing Noise Field and Its Effects on Laminar Boundary Layer Transition, Volume II—Data Compilation. NASA CR-178217, March 1987. [Referenced in section 1.6.10]

Boeing Commercial Airplane Company: Flight Survey of the 757 Wing Noise Field and Its Effects on Laminar Boundary Layer Transition, Volume III—Extended Data Analysis. NASA CR-178419, March 1988. [Referenced in section 1.6.10]

Brooks, C. W., Jr.; and Harris, C. D.: Results of LFC Experiment on Slotted Swept Supercritical Airfoil in Langley's 8-Foot Transonic Pressure Tunnel. NASA CP-2487, 1987, pp. 453-469. [Referenced in section 2.5]

Campbell, R. L.; Waggoner, E. G.; and Phillips, P. S.: Design of a Natural Laminar Flow Wing for a Transonic Corporate Transport. AIAA Paper 86-0314, 1986. [Referenced in section 1.6.9]

Carmichael, B. H.; Whites, R. C.; and Wisma, R. E.: Low Drag Boundary Layer Suction Experiments in Flight on the wing Glove of an F94-A Airplane. Northrop Aircraft, Inc., Report No. BLC-102, August 1957. [Referenced in section 2.2]

Carmichael, B. H.; Whites, R. C.; and Pfenninger, W.: Low Drag Boundary Layer Suction Experiments in Flight on the Wing Glove of an F94-A Airplane—Phase III – Laminar Suction Airfoil Tolerances. Northrop Aircraft, Inc., Report No. BLC-101, September 1957. [Referenced in section 2.2]

Doty, Wayne A.: Flight Test Investigation of Certification Issues Pertaining to General-Aviation-Type Aircraft with Natural Laminar Flow. NASA CR-181967, 1990. [Referenced in section 1.2]

Douglas Aircraft Company: Laminar Flow Control Leading Edge Glove Flight Test Article Development. NASA CR-172137, 1984. [Referenced in section 2.4]

Etchberger, F. R.: LFC Leading Edge Glove Flight Test-Aircraft Modification Design, Test Article Development, and System Integration. NASA CR-172136, 1983. [Referenced in section 2.4]

Fowell, L. R.; and Antonatos, P. P.: Laminar Flow Flight Test Results on the X-21A. AGARDograph 97, Part 2, May 1965. [Referenced in section 2.3]

George-Falvy, D.: Laminar Flow Test Installation in the Boeing Research Wind Tunnel. AIAA Paper 90-1425, June 1990. [Referenced in section 2.6]

Gray, W. E.; and Fullam, P. W. J.: Comparison of Flight and Tunnel Measurements of Transition on a Highly Finished Wing (King Cobra). RAE Report Aero 2383, 1945. [Referenced in section 1.6.5]

Groth, E. E.; Carmichael, B. H.; Whites, P. C.; and Pfenninger, W.: Low Drag Boundary Layer Suction Experiments in Flight on the Wing Glove of an F94-A Airplane—Phase II – Suction Through 69 Slots. Northrop Aircraft, Inc., Report No. BLC-94, February 1957. [Referenced in section 2.2]

Harvey, W. D.; and Pride, J. D.: The NASA Langley Laminar Flow Control Airfoil Experiment. AIAA Paper 82-0567, March 1982. [Referenced in section 2.5]

Henke, R.; Munch, F. X.; and Quast, A.: Natural Laminar Flow: A Wind Tunnel Test Campaign and Comparison with Flight Test Data. AIAA Paper 90-3045-CP, 1990. [Referenced in section 1.5]

Holmes, Bruce J.: Natural Laminar Flow Hits Smoother Air. Aerospace America, July 1985. [Referenced in section 1.1]

Holmes, Bruce J.; Coy, Paul F.; Yip, Long P.; Brown, Philip W.; and Obara, Clifford J.: Natural Laminar Flow Data from Full Scale Flight and Wind Tunnel Experiments. AIAA 8th Annual General Aviation Technology Fest, Wichita, Kansas, November 13-14, 1981. [Referenced in section 1.1]

Holmes, B. J.; and Obara, C. J.: Observations and Implications of Natural Laminar Flow on Practical Airplane Surfaces. ICAS 82-5.1.1, 1982. [Referenced in section 1.1]

Holmes, Bruce J.; Obara, Clifford J.; and Yip, Long P.: Natural Laminar Flow Experiments on Modern Airplane Surfaces. NASA TP-2256, 1984. [Referenced in section 1.1]

Holmes, Bruce J.: Progress in Natural Laminar Flow Research. AIAA/NASA General Aviation Technology Conference paper, Hampton, Virginia, July 10-12, 1984. [Referenced in section 1.1]

Holmes, Bruce J.; Obara, Clifford J.; Martin, Glenn L.; and Domack, Christopher S.: Manufacturing Tolerances for Natural Laminar Flow Airframe Surfaces. SAE 850863, 1985. [Referenced in section 1.1]

Horstmann, K. H.; Redeker, G.; Quast, A.; Dressler, U.; and Bieler, H.: Flight Tests with a Natural Laminar Flow Glove on a Transport Aircraft. AIAA Paper 90-3044-CP, 1990. [Referenced in section 1.5]

Khalid, M.; Jones, D. J.; and Eggleston, B.: Wind Tunnel Results and Numerical Computations for the NAE/de Havilland Series of Natural Laminar Flow Airfoils. CASI 1st Canadian Symposium on Aerodynamics, Ottowa, Canada, December 4-5, 1989, pp. 2-1 to 2-17. [Referenced in section 1.6.11]

Khalid, M.; and Jones, D. J.: A Summary of Transonic Natural Laminar Flow Airfoil Development at NAE. NAE-AN-65, 1990. [Referenced in section 1.6.11]

Kosin, Ruediger E.: Laminar Flow Control by Suction as Applied to the X-21A Airplane. Journal of Aircraft, September-October 1965, pp. 384-390. [Referenced in section 2.3]

Maddalon, Dal V.; and Braslow, Albert L.: Simulated-Airline-Service Flight Tests of Laminar-Flow Control with Perforated Surface Suction System. NASA TP-2966, 1990. [Referenced in section 2.4]

McGhee, Robert J.; Viken, Jeffrey K.; Pfenninger, Werner; Beasley, William D.; and Harvey, William D.: Experimental Results for a Flapped Natural-Laminar-Flow Airfoil with High Lift/Drag Ratio. NASA TM-85788, 1984. [Referenced in section 1.2]

Meyer, Robert R., Jr.; and Jennett, Lisa A.: In-Flight Surface Oil Flow Photographs with Comparison to Pressure Distribution and Boundary-Layer Data. NASA TP-2395, 1985. [Referenced in section 1.3]

Meyer, Robert R.; Trujillo, Bianca M.; and Bartlett, Dennis W.: F-14 VSTFE and Results of the Cleanup Flight Test Program. Research in Natural Laminar Flow and Laminar Flow Control, NASA CP-2487, 1987, pp. 819-844. [Referenced in section 1.4]

Montoya, Lawrence C.; Steers, Louis L.; Christopher, David; and Trujillo, Bianca: F-111 TACT Natural Laminar Flow Glove Flight Results. NASA CR-2208, 1981. [Referenced in section 1.3]

Murri, Daniel G.; and Jordan, Frank L.: Wind-Tunnel Investigation of a Full-Scale General Aviation Airplane Equipped with an Advanced Natural Laminar Flow Wing. NASA TP-2772, 1987. [Referenced in section 1.2]

Murri, Daniel G.; Jordan, Frank L., Jr.; Nelson, Randy; and Davis, Patrick J.: Wind-Tunnel Investigation of a General Aviation Airplane Equipped with a High Aspect-Ratio, Natural-Laminar-Flow Wing. SAE 871019, 1988. [Referenced in section 1.2]

Nitsche, W.; and Szodruch, J.: Concepts and Results for Laminar Flow Research in Wind Tunnel and Flight Experiments. ICAS 90-6.1.4, 1990. [Referenced in section 1.5]

Obara, Clifford J.; and Holmes, Bruce J.: Flight-Measured Laminar Boundary-Layer Transition Phenomena Including Stability Theory Analysis. NASA TP-2417, 1985. [Referenced in section 1.1]

Obara, Clifford J.; and Holmes, Bruce J.: Roughness and Waviness Requirements for Laminar Flow Surfaces. Langley Symposium on Aerodynamics, vol. 1, 1986, pp. 519-537. [Referenced in section 1.1]

Ostowari, C.; and Naik, D. A.: An Experimental Study of a General Aviation Single-Engine Aircraft Utilizing a Natural Laminar Flow Wing. SAE 850861, 1985. [Referenced in section 1.6.7]

Parikh, P. G.; Lund, D. W.; George-Falvy, D.; and Nagel, A. L.: Hybrid Laminar Flow Control Tests in the Boeing Research Wind Tunnel. SAE 901978, October 1990. [Referenced in section 2.6]

Pfenninger, W.; Groth, E. E.; Carmichael, B. H.; and Whites, R. C.: Low Drag Boundary Layer Suction Experiments in Flight on the Wing Glove of an F94-A Airplane—Phase I – Suction Through 12 Slots. Northrop Aircraft, Inc., Report No. BLC-77, April 1955. [Referenced in section 2.2]

Pfenninger, W.: Flow Phenomena at the Leading Edge of Swept Wings. AGARDograph 97, Part 1, May 1965. [Referenced in section 2.3]

Pfenninger, Werner: Investigations on Reductions of Friction on Wings, in Particular by Means of Boundary Layer Suction. NACA TM-1181, August 1947. [Referenced in section 2.1]

Plascott, R. H.; Higton, D. J.; Smith, F.; and Bramwell, A. R.: Flight Tests on Hurricane II, Z.3687 Fitted with Special Wings of 'Low Drag' Design. British R&M 2546, 1946. [Referenced in section 1.6.4]

Plascott, R. H.: Profile Drag Measurements on Hurricane II Z.3687 Fitted with Low-Drag Section Wings. RAE Report Aero 2153, 1946. [Referenced in section 1.6.4]

Quick, J. W.: Laminar Flow Control Demonstration Program Final Report—LFC Manufacturing Techniques. Northrop Aircraft Company, Report No. NOR-61-142, March 1964. [Referenced in section 2.3]

Redeker, G.; Horstmann, K. H.; Koster, H.; Thiede, P.; and Szodruch, J.: Design of a Natural Laminar Flow Glove for a Transport Aircraft. AIAA Paper 90-3043-CP, 1990. [Referenced in section 1.5]

Redeker, G.; Horstmann, K. H.; Koster, H.; and Quast A.: Investigations on High Reynolds Number Laminar Flow Airfoils. Journal of Aircraft, vol. 25, no. 7, July 1988. [Referenced in section 1.5]

Rozendaal, R. A.: Variable-Sweep Transition Flight Experiment (VSTFE) —Stability Code Development and Clean-Up Glove Data Analysis. Research in Natural Laminar Flow and Laminar Flow Control, NASA CP-2487, 1987, pp. 845-860. [Referenced in section 1.4]

Rozendaal, R. A.: Natural Laminar Flow Flight Experiments on a Swept-Wing Business Jet—Boundary-Layer Stability Analysis. NASA CR-3975, 1985. [Referenced in section 1.6.8]

Runyan, L. J.; and George-Falvy, D.: Amplification Factors at Transition on an Unswept Wing in Free Flight and on a Swept Wing in a Wind Tunnel. AIAA Paper 79-0267, 1979. [Referenced in section 1.6.6]

Runyan, L. James; and Steers, Louis L.: Boundary Layer Stability Analysis of a Natural Laminar Flow Glove on the F-111 TACT Airplane. Viscous Flow Drag Reduction, Gary R. Hough, ed., AIAA, 1979, pp. 17-32. [Referenced in section 1.3]

Runyan, L. J.; Bielak, G. W.; Behbehani, R.; Chen, A. W.; and Rozendaal, R. A.: 757 NLF Glove Flight Test Results. NASA CP-2487, March 1987. [Referenced in section 1.6.10]

Sewall, William G.; McGhee, Robert J.; Viken, Jeffrey K.; Waggoner, Edgar G.; Walker, Betty S.; and Millard, Betty F.: Wind Tunnel Results for a High-Speed, Natural Laminar-Flow Airfoil Designed for General Aviation Aircraft. NASA TM-87602, 1985. [Referenced in section 1.6.9]

Smith, F.; and Higton, D.: Flight Tests on King Cobra FZ.440 to Investigate the Practical Requirements for the Achievement of Low Profile Drag Coefficients on a 'Low Drag' Aerofoil. ACR Report, R&M 2375, 1950. [Referenced in section 1.6.5]

Stark, W. W.: LFC Summary Flight Test Report. Northrop Aircraft Company, Report No. NOR-61-134, April 1964. [Referenced in section 2.3]

Stuper, J.: Investigation of Boundary Layers on an Airplane Wing in Free Flight. NACA TM-751, 1934. [Referenced in section 1.6.1]

Viken, Jeffrey K.; Pfenninger, Werner; and McGhee, Robert J.: Advanced Natural Laminar Flow Airfoil with High Lift to Drag Ratio. NASA Langley Symposium on Aerodynamics, vol. 1, 1986, pp. 401-414. [Referenced in section 1.2]

Wagner, Richard D.; and Fischer, Michael C.: Fresh Attack on Laminar Flow. Aerospace America, March 1984, pp. 72-76. [Referenced in section 2.4]

Wentz, W. H., Jr.; Nyenhuis, R.; and Ahmed, A.: Natural Laminar Flow Flight Experiments on a Swept-Wing Business Jet. AIAA 2nd Applied Aerodynamics Conference, Seattle, Washington, August 21-23, 1984. [Referenced in section 1.6.8]

Wentz, W. H., Jr.; Ahmed, A.; and Nyenhuis, R.: Further Results of Natural Laminar Flow Flight Test Experiments. SAE 850862, 1985. [Referenced in section 1.6.8]

Wetmore, J. W.; Zalovick, J. A.; and Platt, Robert C.: A Flight Investigation of the Boundary-Layer Characteristics and Profile Drag of the NACA 35-215 Laminar-Flow Airfoil at High Reynolds Numbers. NACA WR L-532, 1941. [Referenced in section 1.6.2]

Whites, R. C.; Sudderth, R. W.; and Wheldon, W. G.: Laminar Flow Control on the X-21. Astronautics and Aeronautics, July 1966. [Referenced in section 2.3]

X-21A Engineering Section, Northrop Corporation: Final Report—LFC Aircraft Design Data Laminar Flow Control Demonstration Program. Northrop Corp., Report No. NOR-67-136, June 1967. [Referenced in section 2.3]

Zalovick, John A.: Flight Investigation of Boundary-Layer and Profile Drag Characteristics of Smooth Wing Sections of a P-47D Airplane. NACA ACR L5H11a, 1945. [Referenced in section 1.6.3]

Zalovick, John A.; and Skoog, R. B.: Flight Investigation of Boundary-Layer Transition and Profile Drag on an Experimental Low-Drag Wing Installed on a Fighter-Type Airplane. NACA WR L-94, 1945.

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13. ABSTRACT *(Maximum 200 words)*

Since the 1930s, there have been attempts to reduce drag on airplanes by delaying laminar to turbulent boundary layer transition. Experiments conducted during the 1940s, while successful in delaying transition, were discouraging because of the careful surface preparation necessary to meet roughness and waviness requirements. The resulting lull in research lasted nearly 30 years.

By the late 1970s, airframe construction techniques had advanced sufficiently that the high surface quality required for natural laminar flow (NLF) and laminar flow control (LFC) appeared possible on production aircraft. As a result, NLF and LFC research became widespread.

This report is an overview of that research. The experiments summarized herein were selected for their applicability to small transonic aircraft. Both flight and wind tunnel tests are included.

The description of each experiment is followed by corresponding references. Part One summarizes NLF experiments; Part Two deals with LFC and hybrid laminar flow control (HLFC) experiments.

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