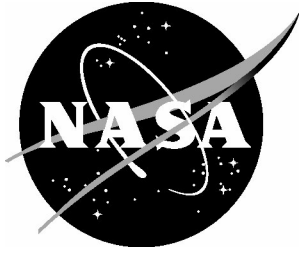


NASA/TM-20220017271



Initial Disturbance Fields for Boundary Layer Transition in Aerospace

Dennis M. Bushnell
Langley Research Center, Hampton, Virginia

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

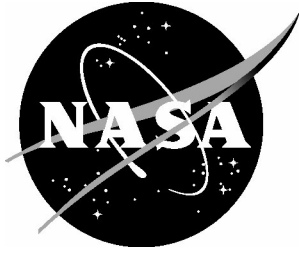
- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>
- Help desk contact information: <https://www.sti.nasa.gov/sti-contact-form/> and select the "General" help request type.

NASA/TM-20220017271



Initial Disturbance Fields for Boundary Layer Transition in Aerospace

Dennis M. Bushnell
Langley Research Center, Hampton, Virginia

The use of trademarks or names of manufacturers in this report is for accurate reporting and does not constitute an official endorsement, either expressed or implied, of such products or manufacturers by the National Aeronautics and Space Administration.

Introduction

The transition from laminar to turbulent flow is of great and fundamental importance in fluid dynamic applications. Skin friction drag, heat transfer, and mass transfer can increase by an order of magnitude between laminar and turbulent flow states. The physics of the myriad transition instability mechanisms have been, and are being exhaustively studied, in terms of both linear and non-linear processes. Each have numerous and possibly interacting manifestations depending upon both the details of the physical problem and the initial and boundary conditions [ref. 1]. Boundary layer transition involves several progressive stages, which result in the ultimate result of turbulent flow. The initial stage is the establishment of the body inviscid and viscous flow fields. A critical input for the transition portion of those flow fields is the multifarious initial disturbance fields, which can be present in the free stream or generated by the vehicle [ref. 2]. These initial disturbance fields are altered by the mean flow in a process termed receptivity and constitute the input for the initial/boundary value transition process. Even low amplitude initial disturbances can, singularly and in combination, affect transition location. There are also a plethora of vehicle geometry boundary conditions which have historically been included in the transition “disturbance fields” including waviness, steps, gaps, roughness, etc. Computational capabilities have advanced via both algorithms and machine capabilities to the point where, given excellent specification of the geometry and initial disturbance fields, the body transition locus could be computed. Thus far, transition prediction for applied problems has been based upon what is termed the e-to-the-N method, a measure of how much linear amplification is computed to have occurred between the commencement of the linear amplification process to where the disturbance growth is sufficient to incite break down into the (observed) non-linear “transitional region.” This is where the flow begins to progress from laminar to turbulent surface heating and friction drag [ref. 3]. Since transition can also occur via a combination of various non-linear bypasses and be affected by levels of initial disturbances, the linear theory e-to-the-N approach has yielded, crudely, two major levels for N: one for “clean” flight experiments and ultra-low disturbance ground facilities [ref. 3] and a much lower level for conventional ground facilities and flight vehicles having, for various reasons, high initial disturbance fields. Overall, the N-factor method should be replaced with direct initial/boundary value computation of the transition process. However, as stated, that requires detailed knowledge of the initial disturbance fields. This knowledge does not yet exist. What would be required in flight is the amplitude, spectra, and mode of all initial and bounding disturbance fields, including vehicle generated disturbances, as a function of latitude, longitude, altitude, and time along the flight path.

Typically, multiple initial disturbance types/sources are present, some capable of producing early non-linear, secondary instabilities and synergistically producing earlier transition [ref. 1]. In the absence of intense/bypass initial disturbance fields, the disturbance fields of most interest to transition are those that are amplified in the normal mode processes. These normal modes can include any or all of the following over a vehicle: Tollmien-Schlichting waves, Mack Second Modes, Cross Flow Disturbance Vortices, Taylor-Gortler Vortices, embedded Kelvin-Helmholtz Waves, and others. The frequency of these disturbance amplification modes varies widely and are the result of vehicle, flow, and flight details. The litany of initial disturbances includes velocity/vorticity fluctuations, temperature and concentration fluctuations, pressure/acoustic fluctuations, particulates, electrostatics, roughness/waviness/gaps/steps, surface dynamic mass transfer, and surface vibrations. The purpose of this report is to review existing information regarding the many initial disturbance fields along with the extant observations regarding their impacts upon boundary layer transition in flight. Suggestions will be made regarding ways forward to provide the requisite increased knowledge regarding initial disturbance fields required to predict transition numerically more accurately, as an initial/boundary layer problem. Such predictions would enable improved design for either delaying transition for drag reduction or advancing it for propulsion and flow separation control. Delaying transition, or laminar flow control, is a major approach to reducing drag on aircraft and thereby reducing their costs and climate impacts. The climate situation is re-energizing interest in laminar flow control. This time not only on wings but also on fuselages. A related application regarding technological effects of atmospheric disturbances upon boundary layer transition is the increasingly important wind turbines generating much of the ever less expensive renewable green energy. For that application, increased initial disturbance levels increase efficiency via earlier transition resulting in less airfoil separation and higher loading.

Stream Turbulence

Fluctuations in vorticity/velocity, temperature/entropy, pressure/acoustics, and species concentrations are usually lumped into the category of atmospheric and stream “turbulence”. It was noted early on in aeronautics in the 1930s that there was a large difference between transition behavior in free flight and in wind tunnels, with transition occurring earlier in wind tunnels. Research at the time traced much of this to greater free stream turbulence in wind tunnels, resulting in the development starting in the 1930s of low turbulence tunnels employing screens and honeycombs in the settling/stagnation chamber. These measures were successful in creating in these special wind tunnels transition behavior closer to flight. Such low disturbance tunnels were generally smaller and mainly used for research vice development. The latter being usually conducted in larger tunnels with higher stream disturbance levels. Ground facility free stream turbulence modes, levels, and impacts vary between subsonic vs. supersonic and above speeds. In subsonic facilities the stream disturbances are usually velocity fluctuations. At transonic speeds and higher the dominant stream disturbance tends to be acoustic modes. At high speeds shock waves can both amplify the incident levels and generate other disturbance modes [ref. 4]. High speed vehicles usually involve nose region bluntness and associated imbedded subsonic regions. Acoustic disturbance modes can reflect off the body and back onto the bow shock and be rereflected, which could allow formation of a richer disturbance spectra [ref. 5]. Also at high speeds, incident concentration fluctuations could incite chemical reactions, further enriching the operative disturbance field external to and initially embedded in the boundary layer. Large scale turbulence can alter the mean flow and hence the transition locus, an expected effect in flight where the turbulence scales are larger.

In the atmosphere and ocean, the usual sources of instabilities/flow dynamics in the air/water column are due to natural convection instabilities in thermally or salinity stratified flows. Usually, the dominant scale of such ambient turbulence is large compared to air vehicle viscous flows. However, turbulence has a wide spectra of motions and there can be dynamic energy content extant down to vehicle viscous flow relevant scales and increased small scale content produced by localized shear layers including weather fronts, the jet stream, ocean currents, atmospheric and benthic boundary layers, and internal wave breaking. Some conventional power generation stations have quite high chimneys whose efflux can create concentration and temperature fluctuations in the atmosphere.

In conventional wind tunnels the sources of stream turbulence depend upon facility design, whether open or closed circuit, speed range, powering, and heating processes. The scale of the stream turbulence in wind tunnels is generally closer to model flow than is the case in flight, hence the same overall turbulence level would, to first order, be expected to have a greater effect on transition in ground facilities. The usual dominant conventional wind tunnel circuit stream turbulence sources are wakes and separated flows and, as stated, can be significantly reduced by settling chamber honeycombs and screens. The mean flow expansion to test conditions reduces test chamber turbulence intensity level except for heated facilities, where enthalpy fluctuations generate stream turbulence during the expansion process. Reduction of stream velocity (aka turbulence) levels usually results in the dominance of the next level of stream disturbance mode – acoustics. The slots and perforations in transonic tunnel walls to control reflected shock impacts generate acoustic energy [ref. 6]. The presence of the model in the test chamber can incite Parker acoustic modes. For supersonic and hypersonic wind tunnels, the dominant stream disturbance is acoustic radiation from the turbulent nozzle wall boundary layers [ref. 7]. Approaches have been developed for high-speed facilities to reinitialize a laminar boundary layer on the nozzle wall near the throat and to design the nozzle to maintain that laminar wall and ultra-low radiated noise condition for as long as possible. Transition data from such high speed “quiet” facilities agree better with flight data than that from conventional “noisy” tunnels [ref. 8]. In the flight case, acoustic fields are generated by the propulsion systems which radiate over the vehicle differently depending upon placement of the propulsive systems and Mach number. Then, at high speeds, there is the multimode dynamics produced by shock waves generated by, or reflecting from, interacting with turbulent flows [ref. 4]. In the design of supersonic transports (SSTs) with laminar flow on the wings, such shock generated disturbance fields can radiate from the fuselage onto the wing. The various boundary layer instability modes are differentially excited/alterd by various stream disturbance modes. As an example, the crossflow instability appears to be not greatly affected by acoustics except in the presence of roughness, a case of combined disturbance field impacts which, as a class of problem, have been little studied but which should be.

Particulates

Historically, particulates have been observed to dampen turbulence (e.g., rain and water sprays). Particulates are used to reduce turbulent drag. However, for transition, particulates can be a major source of initial disturbances via several mechanisms [refs. 2, 9]. These mechanisms include sticking to the surface and becoming a roughness source and producing vorticity while the particle is immersed in the viscous flow (e.g., particle rotation). For the high-speed case, depending on the size of the particle, it can dimple the bow shock during transit through the shock, which then convects downstream with the disturbance frequency given by particle concentration. If large enough, the particle can impact the nose region, producing a roughness via either sticking or gouging. If smaller, the particle can follow streamlines external to the viscous flow, undergo acceleration, and produce a shock wave in the process that strafes the body boundary layer. If smaller still, the particle can follow streamlines and rotate in the boundary layer. Particles can also induce chemical reactions in high-speed flows depending upon their composition and the flow conditions. Stream particle and flow interaction (e.g., effects of rain, snow, ice, dust) has been studied as a source of flight dispersion for weapons [ref 10].

Particles are present in almost all flows unless extraordinary measures are taken to exclude them. At high altitudes, noctilucent clouds can occur at the upper latitudes. These clouds are composed of cosmic dust coated with ice with a diameter the order of .1 micron. For lower altitudes, the particle sources are terrestrial via various mechanisms producing various sizes including volcanic emissions formed at altitude from atmospheric gases, lofted terrestrial dust, solid sulfuric acid from the high-power station stack efflux, rocket exhaust particulates, rain, snow, and ice. In the wind tunnel, there are usually corrosion particulates and if a particle-enabled Laser Doppler Velocimetry (LDV) is used, the LDV particles. In ocean tests, attempts to do laminar flow control were foiled by the particles present in the water column, both animate and inanimate [ref. 11]. Reference 12 indicates that quite small particulates provide a ready mechanism for unit Reynolds Number effects in flight.

Electrostatics

Electrostatics have long created serious problems for aerospace, ranging from loss of life to loss of vehicles [ref. 13]. Mechanisms have included shock, ordnance ignition, fires, explosions, degradation of coatings, sensor, communication, computer, and navigation issues. The possibility of electrostatics, via high frequency discharge of tribo-charged surfaces constituting an initial disturbance field for transition, has been little studied [refs. 14, 15], although there has been considerable interest in using plasma discharges for flow control. Vehicle charging can occur due to tribocharging from flight through atmospheric particulates and from particulates produced in the engine flows. The aircraft charge buildup can exceed 300 kV and is usually discharged using sharp-tipped external devices to avoid information technology (IT) interference. Charge buildup can occur on exposed dielectric surfaces such as windows/canopies, radomes, etc. Discharge is usually via corona mechanisms to adjacent conducting surfaces. Typical discharge frequencies are over 200 kHz, which can, especially at high speeds, constitute a significant initial disturbance field. At very high speeds, the discharge can occur to the plasma flowing over the body. The primary initial disturbance field produced by electrostatics in flight is via high frequency heating of the flow or “temperature spottiness”. The heated gas moves away from the wall causing dynamic streamline deflections.

Vehicle-Generated Disturbance Fields

Vehicles can produce/exhibit varying surface roughness, waviness, gaps, steps, vibrations, etc. that can alter during flight due to increasing loading duration, including the impacts of aerodynamic heating at high speeds [refs. 16, 17]. Also, depending upon thermal protection system details, sublimation and ablation of the surface can occur and alter the vehicle surface over the time of flight. Flight experience with laminar flow control has strongly called out insect impacts and their residue as serious roughness issues accrued during flight. There are technologies under development aimed at reducing these. For transition prediction in flight, these in-flight-produced variations require definitization. Vehicle-propulsion-generated acoustics can, especially at subsonic speeds, affect extensive regions of the vehicle, requiring extensive acoustic computation as a function of vehicle design and operational parameters. At high speeds, details of fuselage surface morphology can generate, usually within turbulent boundary layers, multiple oscillating shock waves which, depending upon vehicle design, can intersect/interact with wing

viscous flows [ref.4]. Study of laminar flow control suction surfaces indicate worrisome acoustic disturbances exiting the suction slots. The X-21 program researched minimization of these disturbances. With pressurized fuselages, airframe air leakage will vary in space and time. Propellor slip streams are also a major problem for laminar flow control. The space shuttle experienced major vehicle-generated disturbance field effects upon transition in flight [ref. 18]. The launch stack had the orbiter lower surface with the thermal protection system tiles mated toward the central hydrogen tank. The hydrogen tank dump line ran between the shuttle lower surface and the hydrogen tank. At KSC with its usual high humidity, during launch preparation the very cold hydrogen dump line would accrete ice. During launch this ice could break off and impact the tiles, causing various levels and locations of surface damage which directly impacted the boundary layer transition/heating during reentry.

Initial Disturbance Field(s) Impacts During Flight

There is a paucity of flight transition experiments with concomitant measurements of initial disturbance fields and their impacts. At high speeds there are some interesting rocket development experiences possibly related to initial disturbance fields. A series of flights with nominally identical vehicles identified the possibility that the variable transition locations observed were due to atmospheric particulate effects. Another series of vehicles with different outer coverings suggested the possibility of electrostatics.

In ref. 19, a hot wire was mounted on the nose of a low-speed glider to measure incident turbulence intensities, which were found to be greater than usually observed in the atmosphere and increased in the presence of clouds, possibly due to the presence of particulates. The transition processes in flight were similar to those in usual higher turbulence wind tunnels, not low disturbance tunnels.

In ref. 20, fluctuating pitot pressure and cone transition data were obtained on a cone mounted ahead of a powered fighter aircraft at subsonic and supersonic conditions. The stream disturbances decreased in level when the vehicle went supersonic, suggesting that disturbances at subsonic flight speeds might have been partially propulsion and airframe generated acoustics radiated forward onto the cone. The measured stream disturbances had appreciable signal out to some 20 kHz. The stream disturbance levels in this flight experiment were the order of those measured in low disturbance ground facilities as were the transition locations. This suggests that low disturbance ground facilities are useful with respect to replicating flight fairly well in the case of a “clean”, low disturbance flight, which are usually research flights where special care has been taken to minimize initial disturbance fields.

In the X-21 laminar flow control (LFC) flight research program [ref. 21] concerning suction LFC on a swept wing, 50-mile visibility was required to avoid effects of atmospheric aerosols upon the performance of the suction LFC.

In ref. 22, flight experiments on a motorized glider with a natural laminar flow (NLF) wing flying through varying free stream turbulence document detailed measurements of the disturbance field and transition processes. The wide-scale spectrum of the atmospheric turbulence produced, from larger scales, unsteady mean flow over the airfoil which accelerated transition, as did the smaller scales. Overall, as mentioned, for a given free stream turbulence intensity, more of the fluctuating energy scales with the vehicle and viscous flow in the wind tunnel than in flight, producing, for a given turbulence intensity measurement, more effect on transition in the wind tunnel than in flight.

In ref. 23, a turboprop aircraft with an NLF wing glove and flight in and out of clouds was studied. Dry clouds did not alter transition, but wet clouds with water particulates did. Transition was often tripped by laminar boundary layer separation.

In ref. 24, transition measurements in flight on a business jet with 27.23 degrees wing sweep angle were analyzed. No observable effect of different engine settings/varying engine noise was noted.

Ref. 25 determined sailplane wings in atmospheric turbulence can bypass the linear amplification mode.

In ref. 26, flow behavior on a laminar glove on a glider during transition development was compared with wind tunnel results. Oblique instability wave trains occurred earlier in the transition process in flight.

Ref. 27 studied roughness and surface morphology changes in flight and their effects on transition.

This section indicates the paucity of data available concerning the impacts, in flight, of stream and vehicle disturbances upon vehicle transition location and behavior. Much of the observed behavior is dependent upon vehicle design details. Zeroth order, these design details dictate the basic instability modes and their combinatorials leading to transition and alter the effects of stream and vehicle disturbance fields. There are few robust general flight

application indications with respect to transition behavior from such limited information considering the rich and interacting physics. This is the fundamental rationale for greatly increased study and documentation with respect to stream and vehicle disturbances in flight so that the transition design problem can be definitively treated as an initial, boundary value problem.

A Suggestion

What is needed to enable utilization of initial disturbance fields in flight for transition prediction, predicting transition as an initial/boundary value problem is data – extensive, “big data” to attempt to at least bound the transition locus given vehicle specifics, a flight path, and a day/date. Sparse initial data sets, regarding atmospheric turbulence levels and particulates for various atmospheric conditions and altitudes, do exist. These can be assembled, accessed, and used to provide initial bounds for those inputs. Careful pre- and post-flight scanning/documentation of vehicle surface morphology would be useful as a first order attempt to bound vehicle-induced and modified initial disturbance fields. A suggested follow-on approach for serious transition research and the effects of initial disturbance fields in flight includes a combination of the following:

1. Using state-of-the-art miniaturized sensors/instruments including optical systems, develop an instrumentation package to measure both free stream turbulence/particulates changes during flight (which were observed to be critical to transition) and associated vehicle surface morphology dynamics. These sensors could be mounted on a large number of flight vehicles employing various flight paths. It is a relatively inexpensive approach to obtain and amplify the limited extant initial disturbance field data for flight and would improve and delineate the bounds of the normal and define the abnormal conditions regarding initial disturbances for flight transition.

2. Conduct a flight research study designed around the available initial disturbance field data sets, to perform detailed experiments to measure both initial disturbance fields and boundary layer transition behaviors along with comparisons to transition prediction computations.

Concluding Remarks

The mean flow conditions in flight can appreciably change day to day, therefore, atmospheric dynamics models should be used to determine excursions from the standard atmospheric tables to estimate flight transition location. Atmospheric turbulence data indicate possible coupling with boundary layer transition up to the order of 40,000 feet, with internal wave breaking events possibly extending this to higher altitudes. Particulates as initial transition disturbance fields could extend up to 70,000 to 80,000 feet. Electrostatics are always a possibility if dialectic outer surfaces are present, enabling charge buildup/discharge from flight through atmospheric particulates. Acoustic fields and surface morphology, including insect remains, are additional common flight disturbance fields. Initial disturbance fields can act upon transition synergistically and the structure/detailed development(s) of the mean flow determines the dominant instability modes, which can have quite different sensitivities to various classes and levels of initial disturbances. That is, boundary layer transition is a system of systems, involving linear and non-linear amplification processes with major variability depending upon the mean flow development details and their varying sensitivities to initial disturbance fields and modal amplifications.

The available data regarding the sensitivity of transition to disturbances in flight indicate the variability and larger scales of atmospheric turbulence for a given turbulence intensity can have different and sizable impacts on the transition process, as can flight through clouds and atmospheric particulates. Surface morphology is another major transition change agent, which can and usually does alter during flight.

Flight disturbance knowledgeability requires sensing exquisitely detailed and continually updated surface morphology, all aspects, and all cogent stream disturbance sources, both atmospheric and vehicle engendered. Many of these requisite initial/boundary condition disturbance field measurement requirements have evidently not been considered either feasible, or important enough thus far to support a serious delineation effort. Therefore, designers cannot (yet) reliably predict transition in flight. Perhaps researchers and engineers can develop work arounds or ways to accommodate current innate shortfalls regarding flight transition prediction. The sensors are now available to gather the requisite data to predict transition as an initial, boundary layer problem.

References

1. Reshotko, Eli, "Transition Issues for Atmospheric Entry", J. Spacecraft and Rockets, V. 45, No. 2, March-April 2008, pp. 161-164.
2. Bushnell, Dennis, "Notes on Initial Disturbance Fields for the Transition Problem", in "Instability and Transition", pp. 217-232, Springer, 1990.
3. Horstman, K.H. et al, "Flight and Wind-Tunnel Investigations on Boundary Layer Transition", J. Aircraft, V. 27, No. 2, Feb. 1990.
4. Anyiwo, J.C. and Bushnell, D.M., "Turbulence Amplification in Shock Wave Boundary Layer Interactions", AIAA J., Vol. 20, 1982, pp.893-899.
5. Morkovin, M.V., "Note on the Assessment of Flow Disturbances at a Blunt Body Traveling at Supersonic Speeds Owing to Flow Disturbances in the Free Stream", J. of Applied Mechanics, June 1960, pp. 223-229.
6. Varner, M.O., "Noise Generation in Transonic Wind Tunnels", AIAA paper 74-633, 1974.
7. Pate, Samuel R., "Effects of Wind-Tunnel Disturbances on Boundary Layer Transition with Emphasis on Radiated Noise, A Review", AIAA paper 80-0431.
8. Beckwith, Ivan E. et al., "Free-Stream Noise and Transition Measurements on a Cone in a Mach 3.5 Pilot Low Disturbance Tunnel", NASA TP-2180.
9. Holden, Michael S., "Studies of Boundary Layer Transition and Surface Roughness Effects in Hypersonic Flow", AFOSR-TR-84-0251, Oct. 1983.
10. Holden M.S. et al., "An Experimental Study of Particle-Induced Convective Heating Augmentation and Surface Roughness Effects in Hypersonic Flow", AIAA paper 76-320, 1976.
11. Lauchle, Gerald C. and Gurney, G.B., "Laminar Boundary Layer Transition on a Heated Underwater Body", J. Fluid Mechanics, V. 144, 1984, pp. 79 – 101.
12. Pearce, Blaine E. et al., "Cloud Particle Induced Boundary Layer Transition on Hemispherically Blunted Bodies in Supersonic Flight", ARAP report No. 460, Dec. 1981.
13. Nanevich, J.E., "Static Electricity Phenomena: Theory and Problems", Conference on Certification of Aircraft For Lightning and Atmospheric, Electricity Hazards, ONERA, Proceedings, Sept. 14-21, 1978.
14. Klein, Enrique J., "Excitation of Boundary Layer Turbulence Through Spark Discharges", NASA Tn-D-6378, May 1971.
15. Velkoff, Henry R. and Ketcham, Jeffrey, "Effect of Electrostatic Field on Boundary Layer Transition", AIAA J., V. 6, No. 7, pp 1381-1383, July 1968.
16. Berkowitz, A.M. et al., "Boundary Layer Transition Flight Test Observations", AIAA paper 77-125. Jan. 1977.
17. Schneider, Steven P., "Flight Data for Boundary-Layer Transition at Hypersonic and Supersonic Speeds", J. Spacecraft and Rockets, V. 36, No. 1, Jan/Feb 1999, pp. 8-20.
18. McGinley, Catherine B. et al, "Review of Orbiter Flight Boundary Layer Transition Data", AIAA paper 2006-2921, 2006.
19. Zanin, B. Yu., "Transition to Turbulence on a Wing in Flight and in a Wind Tunnel at the Same Reynolds Number", Soviet J. Of Applied Physics, V.3, No. 2, Mar/Apr. 1989.
20. Fisher, David F. and Dougherty, N. Sam Jr., "In Flight Transition Measurement on a 10 Degree Cone at Mach Numbers .5 to 2", NASA TP-1971, June 1982.
21. Stark, W.W. LFC Summary Flight Test Report - Laminar Flow Control Airplane Demonstration Program. Advanced Technology Program System 659 NOR-61-134 (Contract AF 33(600) -42052), Northrop Corp.
22. Reeh, Andreas D., "Natural Laminar Flow Airfoil Behavior in Cruise Through Atmospheric Turbulence", Ph.D. Thesis, Tech. Univ. Darmstadt, <https://tuprints.ulb.tu-darmstadt.de/4123/>
23. Obara, Clifford J. and Holmes, Bruce J., "Flight-Measured Laminar Boundary Layer Transition Phenomena Including Stability Theory Analysis", NASA TP-2417, 1985.
24. Ahmed, A. et al., "In-Flight Boundary Layer Transition Measurements on a Swept Wing", J. Aircraft, V. 26, No. 11, Nov. 1989.

25. Bertolotti, Fabio P., "Effect of Atmospheric Turbulence in a Laminar Boundary Layer", XXVI OSTIV Congress, Technical Soaring, V. XXV, No. 2, April 2001, PP 154-159.
26. Peltzer, Inken, "Comparative In-Flight and Wind Tunnel Investigations of the Development of Natural and Controlled Disturbances in The Laminar Boundary Layer of an Airfoil", Expts. In Fluids, V. 44, Issue 6, pp. 961-972, June 2008.
27. Schneider, Steven P., "Effects of Roughness on Hypersonic Boundary Layer Transition", J. Spacecraft and Rockets, V. 45, No. 2, March-April 2008.