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**RTO AGARDograph 300**
**Flight Test Techniques Series – Volume 23**

**SCI-040**

# Flight Test Measurement Techniques for Laminar Flow

(Les techniques de mesure en vol des écoulements laminaires)

This AGARDograph has been sponsored by the Flight Test Technology Team (FT3) of the Systems Concepts and Integration Panel (SCI) of RTO.

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Edited by D. Fisher, K.H. Horstmann and H. Riedel

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# Flight Test Measurement Techniques for Laminar Flow

## (RTO AG-300 Vol. 23 / SCI-040)

# Executive Summary

The advantages of laminar flow technology have been well known for decades. Experiments in Germany, the United Kingdom, and the United States date back to the 1930's. One application of some of the early research was the use of a laminar flow airfoil on the P-51 fighter aircraft.

Laminar flow can be obtained on an aircraft by shaping the airfoil and creating a favorable pressure gradient resulting in "Natural Laminar Flow," (NLF). Another method, "laminar flow control," (LFC) is to apply active suction through a porous surface, removing the local turbulence disturbances. A third method is to combine the two, using LFC near the leading edge and NLF on the aft portion of the airfoil. This is referred to as "Hybrid Laminar Flow Control."

Laminar flow technology is one that requires flight testing to obtain the proper noise environment, Reynolds number, scale, and environmental conditions. One of the most extensive laminar flow flight tests was performed on the X-21A in the 1960's by Northrop and the U.S. Air Force. Those tests used LFC in which small portions of the boundary layer near the surface were removed with suction through narrow slots in the skin. That technology was not adopted by the transport aircraft manufacturers because of the added weight and complexity of manufacturing and operating the systems, the low cost and availability of fuel at the time, and the lack of a good solution for the insect contamination problem.

However, the capability of manufacturing close tolerances today with computer-controlled milling machines, materials such as perforated titanium, and insect contamination alleviation techniques makes a laminar flow on a transport aircraft a closer reality.

This AGARDograph addresses proven flight test techniques that have been tested and applied over the last several decades. It illustrates the problems required to overcome, suggests equipment and instrumentation that might be used, and discusses environmental effects and flight test procedures. It provides options for obtaining good results using different flight test techniques, from very simple to more complex.

# Les techniques de mesure en vol des écoulements laminaires

## (RTO AG-300 Vol. 23 / SCI-040)

# Synthèse

Les avantages des technologies de l'écoulement laminaire sont connus depuis des décennies. Les expériences réalisées en Allemagne, au Royaume-Uni et aux Etats-Unis datent des années 1930. L'une des applications de ces premiers travaux de recherche a été l'adoption d'un profil de voilure à écoulement laminaire sur l'avion de combat P-51.

En aéronautique, l'écoulement laminaire peut être obtenu en façonnant le profil de telle manière à créer un gradient de pression qui produit un « écoulement laminaire naturel » (NLF). Une autre méthode, appelée « contrôle de l'écoulement laminaire » (LFC) consiste à créer une dépression active à travers une surface poreuse, éliminant ainsi les perturbations locales occasionnées par les tourbillons. Une troisième méthode représente une combinaison des deux premières, et applique le LFC à une zone proche du bord d'attaque et le NLF à la partie arrière du profil de voilure. Cette méthode s'appelle « contrôle hybride de l'écoulement laminaire ».

La mise au point des technologies de l'écoulement laminaire nécessite la réalisation d'essais en vol afin d'obtenir les conditions de milieu sonore, de nombre Reynolds, d'échelle et d'environnement appropriées. L'un des essais en vol de l'écoulement laminaire le plus coûteux a été réalisé sur le X-21A dans les années soixante par Northrop et l'US Air Force. Ces essais ont fait appel au LFC. En l'occurrence, des petits morceaux de la couche limite proche de la surface ont été enlevés par la technique de dépression active à travers des fentes étroites pratiquées dans le revêtement. Cette technique n'était pas adoptée par les constructeurs d'avions de transport en raison du poids supplémentaire et de la complexité de la fabrication et de l'exploitation des systèmes, ainsi que du coût modéré du carburant et de sa grande disponibilité à l'époque, et du problème de contamination par les insectes.

Cependant, aujourd'hui, avec les tolérances serrées autorisées par les fraiseuses numériques, les matériaux tels que le titane perforé, et les techniques d'atténuation de la contamination causée par les insectes, l'application du concept d'écoulement laminaire aux avions de transport paraît de plus en plus faisable.

Cette AGARDographie examine des techniques d'essais en vol éprouvées, qui ont été essayées et mises en œuvre au cours des dernières décennies. Elle fait ressortir les problèmes qui sont à résoudre, propose différents équipements et de l'instrumentation susceptibles d'être mis en œuvre, et examine les effets sur l'environnement, ainsi que les procédures d'essais en vol. Elle présente différentes options de techniques d'essais en vol, permettant d'obtenir de bons résultats, allant du très simple au plus complexe.

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# Nomenclature

## Acronyms

| | |
|---|---|
| AC, ac | Alternating current |
| ACEE | Aircraft energy efficiency program |
| AGL | Above ground level |
| ALT | Attachment line transition |
| ATC | Air traffic control |
| ATTAS | Advanced Technologies Testing Aircraft System |
| CFC | Carbon fiber composite |
| CFD | Computational Fluid Dynamics |
| CFI | Crossflow instability |
| DAST | Drone for aerostructural testing |
| DC, dc | Direct current |
| DLR | Deutsches Zentrum für Luft- und Raumfahrt |
| DNW | Deutsch-Niederländischer Windkanal |
| FAA | Federal Aviation Authority (U.S.) |
| FBPF | Fan blade passing frequency |
| F. S. | Fuselage station |
| FTF | Flight test fixture |
| GASP | Global atmospheric sampling program |
| HARV | High Alpha Research Vehicle |
| HLF | Hybrid laminar flow |
| HLFC | Hybrid laminar flow control |
| ICBM | Intercontinental ballistic missile |
| IR | Infrared |
| KIAS | Knots indicated airspeed |
| KKK | Kryo-Windkanal Köln |
| LC | Liquid crystal |
| LDA | Laser Doppler anemometer |
| LEFT | Leading-edge flight test |
| LF | Laminar flow |
| LFC | Laminar flow control |
| LSTM | Lehrstuhl für Strömungsmechanik der Universität Erlangen |
| LWK | Laminarwindkanal Stuttgart |
| L2F | Laser two-focus anemometer |
| MMO | Maximum operating Mach number |
| MOSFET | Metal-oxide-semiconductor field effect transistor |
| NIST | National Institute of Standards and Technology |
| NLF | Natural laminar flow |
| O. D. | Outside diameter |

| | |
|---|---|
| PCM | Pulse code modulation |
| PGME | Propylene glycol monomethyl ether |
| PRT | Platinum resistance thermometer |
| PSD | Power spectral density |
| PSE | Parabolized stability equations |
| RFI | Radio frequency interference |
| RMS | Root-mean-square |
| SPL | Sound pressure level |
| TACT | Transonic aircraft technology |
| TDC | Top dead center |
| TP | Test point |
| T-S | Tollmien-Schlichting |
| TSI | Tollmien-Schlichting instability |
| U.K. | United Kingdom |
| U.S. | United States |
| USAF | United States Air Force |
| VSTFE | Variable-Sweep Transition Flight Experiment |

## Symbols

| | |
|---|---|
| $A$ | Calibration constant in King's Law |
| $a$ | Calibration constant in King's Law |
| $B$ | Calibration constant in King's Law |
| B. L. | Boundary layer |
| $b$ | Width of disturbance or step, calibration constant in King's Law |
| $C_D$ | Drag coefficient |
| $C_L$ | Lift coefficient |
| $C_p$ | Pressure coefficient |
| $c$ | Wing or HLF nacelle fan cowl chord length |
| $C_d$ | Section drag coefficient |
| $C'_f$ | Skin friction coefficient |
| $C_l$ | Section lift coefficient |
| dB | Decibel |
| E | Anemometer output bridge voltage |
| $E_{ac}$ | Aircraft electrical power voltage |
| $E$ | Output voltage |
| $\overline{E}$ | Output voltage mean value |
| $e'$ | Fluctuating value of output voltage |
| $f$ | Frequency |
| $G_x(f)$ | Power spectral density function |
| $g$ | Standard gravitational constant |

| | |
|---|---|
| H | Harmonic frequency |
| $H$, $h$ | Altitude |
| h | Disturbance or step height, 0.06 mm |
| $h_p$ | Pressure altitude |
| $I$ | Current amperage |
| $k$ | Thermal conductivity of the air |
| $k_{crit}$ | Critical disturbance height |
| L | Lift |
| M | Mach number |
| $Ma_\infty$ | Free-stream flight Mach number |
| $N_1$ | Engine fan speed, percent of maximum |
| $N_{1C}$ | Corrected engine fan speed |
| $n$ | Amplification factor exponent, exponent in King's Law |
| $p_{pr}/p_{t\infty}$ | Traversing probe pressure normalized by free-stream total pressure |
| $p$ | Pressure |
| $p'$ | Fluctuating pressure |
| $p_{t,\infty}$ | Free-stream total pressure |
| $p_{t,\text{probe}}$ | Probe total pressure |
| $q$, $q_\infty$ | Free-stream dynamic pressure |
| $R$ | Resistance |
| $\text{Re}_c$ | Reynolds number based on chord length, c |
| $\text{Re}_{k,\,crit}$ | Reynolds number based on critical disturbance height |
| $\text{Re}_{Tr}$ | Reynolds number based on end of transition |
| $\text{Re}_{tr}$ | Reynolds number based on beginning or onset of transition |
| $\text{Re}_w$ | Reynolds number based on sensor wire diameter, w |
| $\text{Re}_x$ | Reynolds number based on longitudinal coordinate, x |
| $\text{Re}_\Theta$ | Reynolds number based on attachment line momentum thickness, $\Theta$ |
| $t_a$ | Temperature of the airflow |
| $Tr_f$ | Boundary layer transition front location = $(x_{tr}/c + x_{Tr}/c)/2$ |
| $t_w$ | Nacelle wall temperature, temperatures of the hot-wire sensor |
| $t_{t\infty}$ | Free-stream total temperature |
| $Tu$ | Turbulence intensity |
| $Tu(u')$ | Turbulence intensity based on velocity fluctuation, $u'$ |
| $Tu(v')$ | Turbulence intensity based on velocity fluctuation, $v'$ |
| $t$ | Temperature |
| $u_k^*$ | Shear stress velocity |
| $U$ | Local velocity |
| U | Flow velocity, velocity near edge of boundary layer |
| $U_\infty$ | Free-stream velocity, true airspeed |

| | |
|---|---|
| $U_k$ | Velocity within the boundary layer at the disturbance height |
| $u/U$ | Local to free-stream velocity ratio |
| $u, v, w$ | Velocity components in the direction of the axes of the rectangular Cartesian system x, y, z |
| $u', v', w'$ | Velocity fluctuations associated with u, v, w respectively |
| $V$ | Aircraft velocity |
| $V_c$ | Calibrated velocity |
| $x_{Tr}$ | Location at end of boundary layer transition |
| $x_{tr}$ | Location at onset of boundary layer transition |
| $x$ | Longitudinal coordinate measured from fan cowl leading edge |
| $x, y, z$ | Rectangular Cartesian coordinates |
| $x/c$ | Normalized longitudinal coordinate |
| $x/L$ | Distance from cone apex normalized by cone length |
| $\alpha$ | Angle of attack |
| $\alpha_h$ | Heat transfer coefficient |
| $\beta$ | Yaw angle |
| $\Delta c_l$ | Lift coefficient increment |
| $\Delta p$ | Differential pressure |
| $\Delta t$ | Temperature error |
| $\varepsilon_\varphi$ | Directional radiation |
| $\eta_F$ | Flap angle |
| $\theta$ | Circumferential angle |
| $\Theta$ | Momentum thickness |
| $\lambda$ | Heat conductivity of the fluid |
| $\rho$ | Density |
| $\overline{(\rho u)'}/\overline{(\rho U_\infty)}$ | Normalized mass flow fluctuations |
| $\sigma$ | Sea level density ratio of the air, root-mean-square (RMS) gust velocity |
| $\tau_{0k}$ | Wall shear stress at the disturbance location |
| $\tau_w$ | Wall shear stress |
| $\bar{\tau}_w$ | Mean shear stress |
| $\tau'_w$ | Fluctuating value of shear stress |
| $\nu$ | Kinematic viscosity |
| $\varphi$ | Wing leading edge sweep angle, circumferential angle |
| $\Omega$ | Resistance, Ohms |

## Subscripts

| | |
|---|---|
| IAS | Indicated airspeed |
| $\infty$ | Free-stream conditions |
| $\rho$ | Density |

# AGARDograph Series 160 and 300

The Systems Concepts and Integration (SCI) Panel has a mission to distribute knowledge concerning advanced systems, concepts, integration, engineering techniques, and technologies across the spectrum of platforms and operating environments to assure cost-effective mission area capabilities. Integrated defence systems, including air, land, sea, and space systems (manned and unmanned) and associated weapon and countermeasure integration are covered. Panel activities focus on NATO and national mid- to long-term system level operational needs. The scope of the Panel covers a multidisciplinary range of theoretical concepts, design, development, and evaluation methods applied to integrated defence systems.

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These tasks were recognized and addressed by the former AGARD organization of NATO in the form of two AGARDograph series. The team continues this important activity by adding to the series described below.

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At the end of each AGARDograph 160 Flight Test Instrumentation Series and AGARDograph 300 Flight Test Techniques Series volume is an annex listing all of the monographs published in both series.

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Liquid crystal
Oil flow
Raised-pitot
Separation
Sublimating chemicals
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**14. Abstract**

This AGARDograph provides information on flight test techniques, instrumentation, environmental effects, and flight procedures that have been used successfully in laminar flow research. Many techniques are described for measuring the location of boundary layer transition in-flight, from the very simple to the more complex. References to previous works are included for readers to explore. Specific instrumentation for flight is described and the unique environmental effects of flight noted. Procedures for flight test maneuvers are also included.

Techniques discussed cover both local and global measurements. Some of the local flow techniques include surface temperatures, hot-film and hot-wire anemometry, raised-pitot, and traversing surface pitot. Global flow techniques include the infrared imaging, oil flow, liquid crystal, sublimating chemicals, and emitted fluid techniques. Some of the environmental concerns discussed include atmospheric particulate (ice crystals) and turbulence. Flight test procedures for infrared imaging and for insect contamination avoidance are described.

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