

TECHNICAL REPORT



Information technology – Sensor network – Guidelines for design in the
aeronautics industry: active air-flow control

(<https://standards.iteh.ai>)
Document Preview

[ISO/IEC TR 22560:2017](https://standards.iteh.ai/catalog/standards/iso/d8946a55-146b-4ee0-a5cd-245dd2c924ee/iso-iec-tr-22560-2017)

<https://standards.iteh.ai/catalog/standards/iso/d8946a55-146b-4ee0-a5cd-245dd2c924ee/iso-iec-tr-22560-2017>





THIS PUBLICATION IS COPYRIGHT PROTECTED
Copyright © 2017 ISO/IEC, Geneva, Switzerland

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying and microfilm, without permission in writing from either IEC or IEC's member National Committee in the country of the requester. If you have any questions about ISO/IEC copyright or have an enquiry about obtaining additional rights to this publication, please contact the address below or your local IEC member National Committee for further information.

IEC Central Office
3, rue de Varembe
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
Fax: +41 22 919 03 00
info@iec.ch
www.iec.ch

About the IEC

The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes International Standards for all electrical, electronic and related technologies.

About IEC publications

The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigenda or an amendment might have been published.

IEC Catalogue - webstore.iec.ch/catalogue

The stand-alone application for consulting the entire bibliographical information on IEC International Standards, Technical Specifications, Technical Reports and other documents. Available for PC, Mac OS, Android Tablets and iPad.

IEC publications search - www.iec.ch/searchpub

The advanced search enables to find IEC publications by a variety of criteria (reference number, text, technical committee,...). It also gives information on projects, replaced and withdrawn publications.

IEC Just Published - webstore.iec.ch/justpublished

Stay up to date on all new IEC publications. Just Published details all new publications released. Available online and also once a month by email.

Electropedia - www.electropedia.org

The world's leading online dictionary of electronic and electrical terms containing 20 000 terms and definitions in English and French, with equivalent terms in 16 additional languages. Also known as the International Electrotechnical Vocabulary (IEV) online.

IEC Glossary - std.iec.ch/glossary

65 000 electrotechnical terminology entries in English and French extracted from the Terms and Definitions clause of IEC publications issued since 2002. Some entries have been collected from earlier publications of IEC TC 37, 77, 86 and CISPR.

IEC Customer Service Centre - webstore.iec.ch/csc

If you wish to give us your feedback on this publication or need further assistance, please contact the Customer Service Centre: csc@iec.ch.

standards.iteh.ai
<https://standards.iteh.ai/catalog/standards/iso/d8946a55-146b-4ee0-a5cd-245dd2c924ee/iso-iec-tr-22560-2017>

<https://standards.iteh.ai/catalog/standards/iso/d8946a55-146b-4ee0-a5cd-245dd2c924ee/iso-iec-tr-22560-2017>

TECHNICAL REPORT



**Information technology – Sensor network – Guidelines for design in the
aeronautics industry: active air-flow control**

*iteh Standards
(<https://standards.iteh.ai>)
Document Preview*

[ISO/IEC TR 22560:2017](https://standards.iteh.ai/catalog/standards/iso/d8946a55-146b-4ee0-a5cd-245dd2c924ee/iso-iec-tr-22560-2017)

<https://standards.iteh.ai/catalog/standards/iso/d8946a55-146b-4ee0-a5cd-245dd2c924ee/iso-iec-tr-22560-2017>

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 35.110; 49.060

ISBN 978-2-8322-4920-8

Warning! Make sure that you obtained this publication from an authorized distributor.

CONTENTS

FOREWORD.....	5
INTRODUCTION.....	6
1 Scope.....	7
2 Normative references	7
3 Terms and definitions	7
4 Symbols (and abbreviated terms)	9
5 Motivations for active air-flow control (AFC).....	11
5.1 Skin drag	11
5.2 Approaches for Aircraft Skin Drag Reduction	12
6 Objectives	13
6.1 General.....	13
6.2 Fuel efficiency	13
6.3 Hybrid dense wired-wireless sensor and actuator networks.....	13
6.4 Standardized and service oriented wireless sensor architecture.....	13
6.5 Re/auto/self- configuration	13
6.6 Communication protocols and scalability.....	13
6.7 Smart actuation profiles and policies.....	14
6.8 High rate sensor measurement, synchronous operation and data compression	14
6.9 Troubleshooting and fail safe operation	14
6.10 Enabling of wireless communication technologies in aeronautics industry.....	14
6.11 Integration of wireless technologies with the internal aeronautical communication systems	14
6.12 Design of bidirectional wireless transmission protocols for relaying of aeronautical bus communication traffic	14
6.13 Matching of criticality levels of aeronautics industry	14
6.14 Internetworking and protocol translation between wireless and wireline aeronautical networks	14
7 System description	15
7.1 Overview of system operation	15
7.2 Patch design.....	16
7.3 Internal aeronautics network	17
8 Micro-sensors and actuators.....	18
8.1 Micro-sensors	18
8.2 Actuators	19
9 High level architecture for aeronautical WSANs.....	21
9.1 Bubble concept.....	21
9.2 Layered model	21
9.3 Mapping to ISO/IEC 29182 Sensor Networks Reference Architecture (SNRA).....	23
10 Requirements for AFC design.....	28
10.1 Sensing and actuation	28
10.1.1 BL position detection and space-time resolution	28
10.1.2 Efficient flow control actuation	28
10.1.3 Patch intra and inter-communication	29
10.1.4 Patch sensor data pre-processing, fusion, management and storage.....	29
10.1.5 Patch configuration, redundancy, and organization	29
10.1.6 Sensors synchronicity.....	30

10.1.7	Low power sensor-actuator (patch) consumption	30
10.1.8	Patch data rate and traffic constraints.....	30
10.1.9	Patch low complexity	30
10.2	Sensor Network Communications.....	31
10.2.1	Interference	31
10.2.2	Wireless range and connectivity	31
10.3	Aeronautical Network and On-Board Systems	31
10.3.1	Full-duplex communications.....	31
10.3.2	Compatibility with avionics internal network (ARINC 664)	31
10.3.3	AFC interface	32
10.3.4	GS interface	32
11	Testing platform and prototype development	32
12	Scalability.....	33
Annex A (informative)	System level simulation	36
A.1	Architecture of the simulator and module description	36
A.1.1	Fluid modelling domain	36
A.1.2	Sensor and actuators configuration: patches	36
A.1.3	Wing design, aircraft configuration, and propagation modelling.....	36
A.1.4	Radio resource management	37
A.2	Simulation metrics	38
A.2.1	AFC metrics.....	38
A.2.2	WSN metrics.....	39
Annex B (informative)	Turbulent flow modeling.....	40
Bibliography	44
Figure 1	– Drag breakdown in commercial aircraft	11
Figure 2	– Boundary layer (BL) transition exemplified with a wing profile	12
Figure 3	– Operation mode of the AFC system.....	15
Figure 4	– Architecture of the AFC system	16
Figure 5	– Array(s) of patches of sensors/actuators	17
Figure 6	– Interaction with internal avionics networks	18
Figure 7	– Flow control actuators classified by function [22].....	20
Figure 8	– Flow control actuators: a) SJA; b) Fliperon.....	21
Figure 9	– HLA mapping AFC system.....	22
Figure 10	– Mapping AFC system to the ISO domain reference architecture view	24
Figure 11	– Mapping AFC system to the ISO layered reference architecture view	25
Figure 12	– Mapping AFC system to the ISO sensor node reference architecture	25
Figure 13	– Mapping AFC system to the ISO physical reference architecture	26
Figure 14	– Prototype implementation AFC system	33
Figure 15	– Data rate vs patch size.....	35
Figure A.1	– Simulator architecture	38
Figure B.1	– Characteristics of turbulent flow with different Reynolds numbers (reproduced from [31])	41

Table 1 – Mapping of AFC system to the HLA layered model	23
Table 2 – Mapping of AFC architecture to ISO architecture entity and functional models.....	27
Table 3 – Mapping of AFC system to ISO architecture interface model	28

iTeh Standards
(<https://standards.iteh.ai>)
Document Preview

[ISO/IEC TR 22560:2017](https://standards.iteh.ai/catalog/standards/iso/d8946a55-146b-4ee0-a5cd-245dd2c924ee/iso-iec-tr-22560-2017)

<https://standards.iteh.ai/catalog/standards/iso/d8946a55-146b-4ee0-a5cd-245dd2c924ee/iso-iec-tr-22560-2017>

INFORMATION TECHNOLOGY – SENSOR NETWORK – GUIDELINES FOR DESIGN IN THE AERONAUTICS INDUSTRY: ACTIVE AIR-FLOW CONTROL

FOREWORD

- 1) ISO (the International Organization for Standardization) and IEC (the International Electrotechnical Commission) form the specialized system for worldwide standardization. National bodies that are members of ISO or IEC participate in the development of International Standards through technical committees established by the respective organization to deal with particular fields of technical activity. ISO and IEC technical committees collaborate in fields of mutual interest. Other international organizations, governmental and non-governmental, in liaison with ISO and IEC, also take part in the work. In the field of information technology, ISO and IEC have established a joint technical committee, ISO/IEC JTC 1.
- 2) The formal decisions or agreements of IEC and ISO on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees and ISO member bodies.
- 3) IEC, ISO and ISO/IEC publications have the form of recommendations for international use and are accepted by IEC National Committees and ISO member bodies in that sense. While all reasonable efforts are made to ensure that the technical content of IEC, ISO and ISO/IEC publications is accurate, IEC or ISO cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
- 4) In order to promote international uniformity, IEC National Committees and ISO member bodies undertake to apply IEC, ISO and ISO/IEC publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any ISO, IEC or ISO/IEC publication and the corresponding national or regional publication should be clearly indicated in the latter.
- 5) ISO and IEC do not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. ISO or IEC are not responsible for any services carried out by independent certification bodies.
- 6) All users should ensure that they have the latest edition of this publication.
- 7) No liability shall attach to IEC or ISO or its directors, employees, servants or agents including individual experts and members of their technical committees and IEC National Committees or ISO member bodies for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication of, use of, or reliance upon, this ISO/IEC publication or any other IEC, ISO or ISO/IEC publications.
- 8) Attention is drawn to the normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
- 9) Attention is drawn to the possibility that some of the elements of this ISO/IEC publication may be the subject of patent rights. ISO and IEC shall not be held responsible for identifying any or all such patent rights.

The main task of the joint technical committee is to prepare International Standards. However, the joint technical committee may propose the publication of a Technical Report when it has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

ISO/IEC TR 22560, which is a Technical Report, has been prepared by subcommittee 41: Internet of Things and related technologies, of ISO/IEC joint technical committee 1: Information technology.

This Technical Report has been approved by vote of the member bodies, and the voting results may be obtained from the address given on the second title page.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

The number of wireless connections is growing exponentially around the world. Wireless communications are expanding to areas previously reluctant to use this type of technology. In the field of aeronautics, wireless intra-avionics applications are just recently gaining acceptance both in industrial and academic arenas. This late adoption is mainly because wireless transmissions have been conventionally associated with reliability and interference issues. Aeronautics applications on board aircraft are highly critical and therefore the inherent randomness of wireless technologies created lots of skepticism, particularly for sensing, monitoring and control of critical aeronautical subsystems. In addition, uncontrolled wireless transmissions can potentially create interference to other aeronautical subsystems, thus leading to malfunctions and unsafe operation. However, recent interference and reliability studies with state-of-the-art wireless standards suggest safe operation and thus the feasibility of a relatively new research area called wireless avionics intra-communications (WAICs). In the last few years, wireless technology has started to be used on board for systems that conventionally used only wire-line infrastructure (i.e., as replacement of cables). It is also being used for applications which are now only possible thanks to the wireless component (e.g., indoor localization, tracking and wireless power transfer). Examples of potential applications of wireless avionics intra-communications are the following: structure health monitoring, avionics bus communications, smoke sensors, interference monitoring, logistics, identification, replacing of cables, fuel tank sensors, automatic route control based on optimized fuel consumption and weather monitoring, automatic turbulence reduction or active air-flow control, EMI (electromagnetic interference) monitoring, and flexible wiring redundancy design.

The avionics industry will experience a wireless revolution in the years to come. The concept of “fly-by-wireless” opens several issues in design, configuration, security, spectrum management, and interference control. There are several advantages in the use of wireless technologies for the aeronautics industry. They permit reduction of cables in aircraft design, thus reducing weight. Reduction of weight also leads to increased payload capacity, longer ranges, faster speeds, and mainly savings in fuel consumption. The reduction of cables can also improve the flexibility of aircraft design (less manpower for designing complex cabling infrastructure). Additionally, wireless technologies can reach places of aircraft that are difficult to reach by cables, while being relatively immune to electrical cable malfunctions. Wireless technology also provides improved configuration and troubleshooting with over-the-air functionalities of modern radio standards.

This document presents the application of wireless sensor and actuator networks for the dynamic tracking and compensation of turbulent flows across the surface of aircraft. Turbulent flow formation and the associated skin drag effect are responsible for the inefficiency of airplane design and thus act as major factors in increased fuel consumption. The area of active air-flow control represents the convergence of several scientific fields such as: fluid mechanics, sensor networks, control theory, computational fluid dynamics, and actuator design. Due to the high speeds experienced by modern commercial aircraft, dense networks of sensors and actuators are necessary to accurately track the formation of turbulent flows and for counteracting their effects by convenient actuation policies. The use of wireless technologies in this field aims to facilitate the management of the information generated by the large number of sensors, and reduce the need for cables to interconnect all the nodes or groups of nodes (patches) in the network. Additionally, the use of the wireless components opens new issues in joint propagation and turbulence flow modelling. This document presents the design principles of active air-flow control systems using dense wireless/wired sensor networks compliant with the ISO sensor network reference architecture (SNRA). Standardized interfaces will help developers create smart cloud avionics applications that will improve fleet management, optimized route traffic, and computation of actuation profiles for different moments of an aircraft mission. This also lies within the context of future technological concepts such as Internet of things, Big Data, and cloud computing.

INFORMATION TECHNOLOGY – SENSOR NETWORK – GUIDELINES FOR DESIGN IN THE AERONAUTICS INDUSTRY: ACTIVE AIR-FLOW CONTROL

1 Scope

This document describes the concepts, issues, objectives, and requirements for the design of an active air-flow control (AFC) system for commercial aircraft based on a dense deployment of wired/wireless sensor and actuator networks. The objective of this AFC system is to track gradients of pressure across the surface of the fuselage of aircraft. This collected information will be used to activate a set of actuators that will attempt to reduce the skin drag effect produced by the separation between laminar and turbulent flows. This will be translated into increased lift-off forces, higher vehicle speeds, longer ranges, and reduced fuel consumption. The document focuses on the architecture design, module definition, statement of objectives, scalability analysis, system-level simulation, as well as networking and implementation issues using standardized interfaces and service-oriented middleware architectures. This document aims to serve as guideline on how to design wireless sensor and actuator networks compliant with ISO/IEC 29182.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO/IEC 29182-2:2013, *Information technology – Sensor networks: Sensor Network Reference Architecture (SNRA) – Part 2: Vocabulary and terminology*

ISO/IEC 29182-3:2014, *Information technology – Sensor networks: Sensor Network Reference Architecture (SNRA) – Part 3: Reference architecture views*

ISO/IEC 29182-4:2013, *Information technology – Sensor networks: Sensor Network Reference Architecture (SNRA) – Part 4: Entity models*

ISO/IEC 29182-5:2013, *Information technology – Sensor networks: Sensor Network Reference Architecture (SNRA) – Part 5: Interface definitions*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO/IEC 29182-2:2013 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org.obp>

3.1
active air-flow control

AFC

ability to manipulate a flow field to improve efficiency or performance adding energy to the flow by an actuator and using a sensor or sensors to adjust, optimize, and turn on/off the actuation policy

3.2
ARINC 664

A664

standard that defines the electrical and protocol specifications (IEEE 802.3 and ARINC 664, Part 7) for the exchange of data between avionics subsystems [1]¹

3.3
boundary layer

BL

region in the immediate vicinity of a bounding surface in which the velocity of a flowing fluid increases rapidly from zero and approaches the velocity of the main stream [2]

3.4
boundary layer separation

detachment of a boundary layer from the surface into a broader wake [3], [4]

3.5
bubble

higher level abstraction of a heterogeneous wireless sensor network with different underlying technologies that enables semantic interoperability between them and with the external world using standardized interfaces and flexible middleware application program interfaces

3.6
computational fluid dynamics

CFD

art of using a computer to predict how gases and liquids flow [5]

3.7
drag

force acting opposite to the relative motion of any object moving with respect to a surrounding fluid [29]

3.8
fly-by-wireless

paradigm where avionics subsystems usually controlled or linked by means of cables will use now a wireless connection

3.9
fuselage

aircraft's main body section that holds crew and passengers or cargo [6]

3.10
laminar flow

flow regime that typically occurs at the lower velocities where the particles of fluid move entirely in straight lines even though the velocity with which the particles move along one line is not necessarily the same as along another line [7]

¹ Numbers in square brackets refer to the Bibliography.

3.11

patch

array of sensors and actuators wired together with a central or distributed control scheme

3.12

Reynolds number

number that characterizes the relative importance of inertial and viscous forces in a flow

Note 1 to entry: It is important in determining the state of the flow, whether it is laminar or turbulent [7].

3.13

shear force

force acting on a substance in a direction perpendicular to the extension of the substance, acting in a direction to a planar cross section of a body [8]

3.14

skin friction drag

effect that arises from the friction of the fluid against the "skin" of the object that is moving through it [30]

3.15

synthetic jet actuator

type of actuator whose main effect is produced by the interactions of a train of vortices that are typically formed by alternating momentary ejection and suction of fluid across an orifice such that the net mass flux is zero [8]

3.16

turbulence

type of flow where the paths of individual particles of fluid are no longer everywhere straight (as in laminar flow) but are sinuous, intertwining and crossing one another in a disorderly manner so that a thorough mixing of fluid takes place [2]

3.17

viscosity

resistance of a fluid to a change in shape, or to the movement of neighbouring portions relative to one another [9]

3.18

wireless avionics intra-communications

type of wireless communications within an aircraft [10]

4 Symbols and abbreviated terms

4.1 Abbreviated terms

AFC	Active air-Flow Control
A664	ARINC 664
AGP	Accelerated Graphics Port
AOC	Airline Operation Control
ARINC	Aeronautical Radio INC.
BL	Boundary Layer
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
GS	Ground Systems
HLA	High-Level Architecture

L0	Level 0 of the aeronautical high-level architecture. Used to transport sensor reading via wireless/wireline infrastructure.
L1	Level 1 of the aeronautical high-level architecture. Used to interconnect several L0 WSNs.
L2	Level 2 of the aeronautical high-level architecture. Used to provide external access to the aeronautical WSN or bubble.
LNSE	Linear Navier-Stokes Equation
LSLI	Link-to-System Level Interface
MCDU	Multifunction Control Display Unit
MEMS	Micro-Electro-Mechanical Systems
SDBD	Single Dielectric Barrier Discharge
<i>SFC</i>	Specific Fuel Consumption
SJA	Synthetic Jet Actuator
UDP	User Datagram Protocol
VL	Virtual Link
WAIC	Wireless Avionics Intra Communications
ZNMF	Zero Net Mass Flux

4.2 Symbols

d	size of a patch
D	drag force
Δ_s	spacing between sensors (spatial sampling spacing)
f	sampling rate
g	gravitational constant
l	characteristic linear dimension of a fluid
L	lift force
$\frac{L}{D}$	lift-to-drag ratio
μ	dynamic viscosity of the fluid
N_a	number of actuators per patch
N_s	number of sensors per patch
N_p	number of patches per wireless sensor network gateway
p	pressure
ρ	density of the fluid
R	range
R_b	wireline nominal data rate
R_c	wireless nominal data rate
r_s	rate per sensor
Re	Reynolds number
\mathbf{u}	flow velocity vector
V	speed of the aircraft
ψ	kinematic viscosity of the fluid
W_{initial}	initial weight of the aircraft
W_{final}	final weight of the aircraft
ξ	data compression ratio inside a patch of sensors and actuators

5 Motivations for active air-flow control (AFC)

5.1 Skin drag

The environmental impact (CO₂ footprint) of the ever-increasing number of flights needs to be reduced. This can be achieved by means of new fuel sources, novel engine technologies and structures, advanced concepts of aircraft morphing (smart materials), improved aerodynamics, and improved air traffic management [34].

The reduction of fuel consumption is important for environmental protection purposes (reduced emissions) as well as for cost reduction. The potential for a 50 % reduction in fuel consumption within the next 15 years can be attained by using a combination of aerodynamic, engine, and structural improvements [11], as expressed by the well-known Breguet range equation:

$$R = \frac{V}{g \times SFC} \times \frac{L}{D} \times \ln\left(\frac{W_{\text{initial}}}{W_{\text{final}}}\right) \quad (1)$$

where V is the velocity of the vehicle, L is the lift force, D is the drag force, SFC is the specific fuel consumption, $\ln(\cdot)$ is the natural logarithm function, g is the gravitational constant, W_{initial} is the initial weight of the aircraft and W_{final} is the final weight of the aircraft. By inspecting the expression in Formula (1) it becomes evident that technologies that reduce aircraft drag and the weight of an empty aircraft are crucial regardless of physical configuration. Aerodynamic drag is known to be one of the main factors contributing to increased aircraft fuel consumption. In [12], a study shows that for a long haul commercial aircraft (325 passengers) a combined reduction of 10 % in both skin friction and induced drag (i.e., the components that roughly contribute around 80 % to the total aerodynamic drag in such type of aircraft) may lead to a 15 % fuel consumption reduction. The drag breakdown of a commercial aircraft shows that skin friction drag and lift-induced drag constitute the two main sources of drag, approximately one half and one third, respectively, of the total drag for a typical long range aircraft in cruise conditions [12][13] (see Figure 1). [ISO/IEC TR 22560:2017](https://standards.iteh.ai/catalog/standards/iso/d8946a55-146b-4ee0-a5cd-245dd2c924ee/iso-iec-tr-22560-2017)

<https://standards.iteh.ai/catalog/standards/iso/d8946a55-146b-4ee0-a5cd-245dd2c924ee/iso-iec-tr-22560-2017>

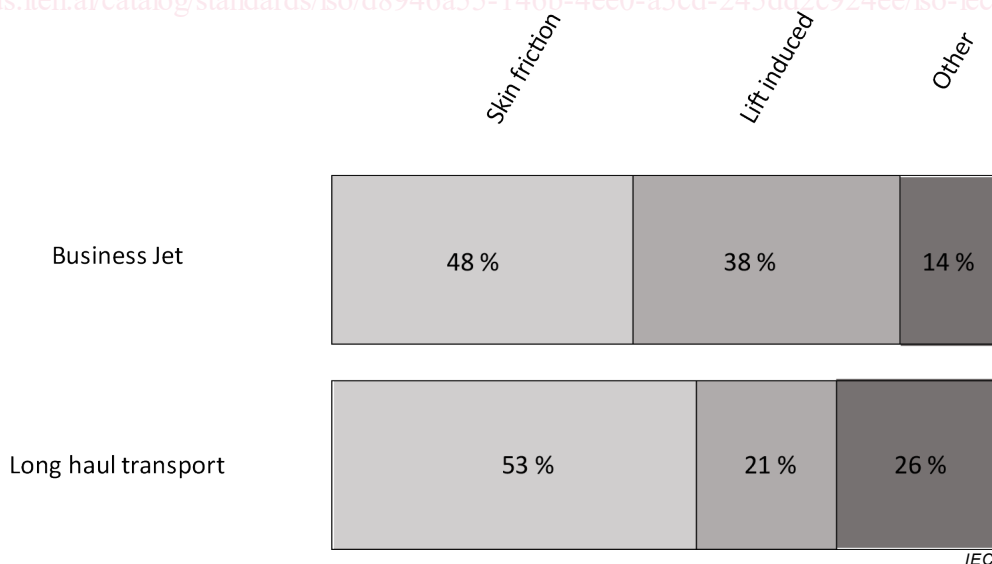


Figure 1 – Drag breakdown in commercial aircraft

Skin friction drag is therefore the main component of the aerodynamic drag. Skin friction arises from the friction of air against the skin of an aircraft in motion. The primary source of skin friction drag during a flight is the boundary layer separation. The boundary layer (BL) is the layer of air moving smoothly in the immediate vicinity of the aircraft (wing, fuselage, tail)

where the flow velocity is lower than that of the free air stream. The proposal of the concept of boundary layer by Prandtl in [28] represented a turning point in the understanding of fluids flowing along the surface of solid objects and the conditions for turbulence formation (boundary layer separation). Inside the BL, viscosity effects are relevant and thus viscous forces dominate. As the flow develops along the surface, the smooth laminar flow is disturbed by the phenomenon of turbulence, which largely increases drag force (Figure 2). In a turbulent flow, viscous and shear forces attempt to counteract each other in a chaotic manner. In this transition, flow separation occurs due to a reversed flow at the surface, increasing drag (particularly pressure drag).

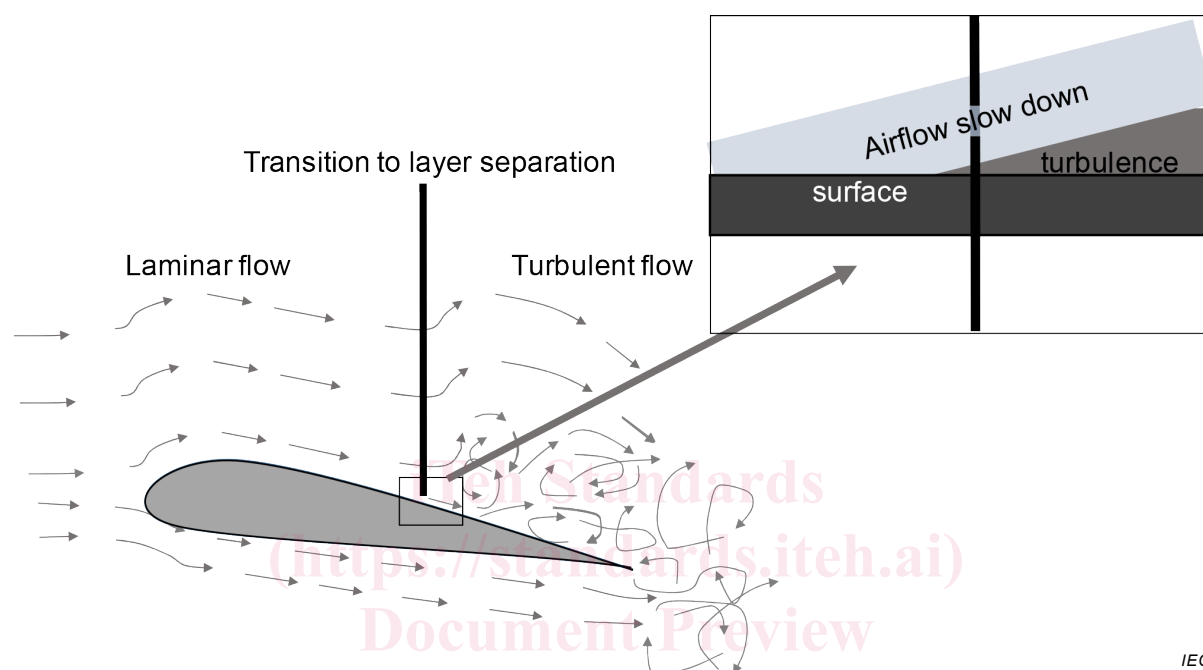


Figure 2 – Boundary layer (BL) transition exemplified with a wing profile

Both BL transition and separation can be controlled in order to reduce drag. Skin friction can be reduced by keeping the flow in the laminar regime, thus reducing the extent of turbulent flow over the air-foil. Preventing flow separation will improve lifting and reduce pressure drag.

5.2 Approaches for aircraft skin drag reduction

The position of the BL transition is affected by local flow disturbances that can be caused by several factors, such as: surface roughness, vibration, heat, air-stream turbulence, etc. There are various approaches to reduce turbulent skin friction, involving different mechanisms, such as:

- reducing turbulent friction drag through riblets;
- deformable active skin using smart materials (compliant walls), or by
- locally delaying the boundary layer transition using vortex generators, such as dimples, holes or synthetic jet actuators (SJAs).

In the case of SJAs, suction from the surface of the wing can be used to remove the low-energy air directly from the BL. Additional momentum (high-energy air) can be achieved in SJA solutions by generating stream wise vortices near the edge of the BL that re-energize the BL flow.

A recent research work in [14] uses SJAs located at key positions on the wing to continuously energize the BL and delay its separation. However, this approach does not use sensors to detect and trace the flow separation point, and is therefore static and proactive in nature. The efficiency of passive flow control is compromised and energy resources are wasted when