INVESTIGATION OF A HEALTH MONITORING METHODOLOGY FOR FUTURE NATURAL LAMINAR FLOW TRANSPORT AIRCRAFT

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Abstract

The health of Natural Laminar Flow aircraft is defined and the functions and contributors of an associated Health Monitoring System are discussed. A methodology is proposed which encompasses four modules: 'monitoring', 'detection', 'diagnosis' and 'recommendation'. For the monitoring module, a Flow Field Based Method (FFBM) and an Aircraft Performance Based Method (APBM) are proposed. Sensors to be used for an FFBM are investigated and selected. Possible sensor arrangements are briefly discussed. The performance distance concept for an APBM is proposed. For the detection module, a Kalman Filter based method is proposed using existing sensors on-board current-generation transport aircraft. Thoughts about future development and implementation of the 'diagnosis' and 'recommendation' modules are discussed.

1 Introduction

The research on laminar flow control including Natural Laminar Flow (NLF) control has been pursued on and off for the past few decades.[1,2,3,4] In recent years, the increasing concerns about the impact of the ever-growing aviation industry on global climate change, and the rocketing rise in oil prices (especially since 2008), have prompted revisiting the concept of laminar flow control for fuel burn reduction.

The NLF concept has been attracting attention from aircraft manufacturers and operators due to its structural simplicity, e.g., there is no need for the myriad of tiny holes and plumbing that are required for suction with the alternative Hybrid Laminar Flow Control (HLFC) concept. Further, advances in aerodynamics, structures and materials applications lend optimism that NLF designs may now be more feasible. For example, composite structures make it practical to achieve a smooth surface,[2] and a leading-edge Krueger flap, deployed from a wing's lower surface, can effectively protect the wing leading edge from potential contamination due to insects.[1] Methods have also been developed to design NLF transport aircraft, including the evaluation of extensive trade studies.[5]

Despite the fact that NLF is a promising technology, it has yet to be incorporated on the wings of today's aircraft. This is usualy attributed to questions as to its practicality from an operational viewpoint as well as its certification by aviation regulators such as the Federal Aviation Administration (FAA). It is the authors' belief that the incorporation of an NLF aircraft Health Monitoring System (HMS) will greatly remedy some of these skepticisms. In fact in 1985, a special workshop was held to discuss possible issues related to certification of laminar flow aircraft.[6] The main drivers behind this workshop were concerns that drag will increase, and stability and control will be affected in cases where loss of laminar flow is experienced.[7,8] From these deliberations, the following findings are worth mentioning:

1) *General operational considerations:* It is recommended to have simple, reliable sensors and displays for use by NLF airplane pilots to determine the extent of laminar flow at any given time during a

flight. The purpose of this information is to assist in real-time flight management.

2) *Aircraft certified without significant NLF:* For aircraft designed with significant NLF over their aerodynamic surfaces but certified without significant NLF, it has to be demonstrated that loss of NLF will produce no significant impact on the certification standards. In this case, the airplane flight manual must provide the pilot the information of airplane characteristics and performance with and without NLF, and what precautions are appropriate with and without NLF.
3) *Aircraft certified with significant NLF:* It is very important that the pilot know when loss of NLF occurs, what actions are necessary to restore laminar flow, or what emergency or diversionary actions are appropriate.
4) *Marketing considerations:* NLF has the potential to save energy, improve economics, increase speed, or extend range. However, if NLF becomes a marketing factor, it should be advertised on the basis of miles per gallon at a given speed.

Based on these findings one can infer that a potential solution to these requirements will be to incorporate an HMS that will either directly or indirectly inform the pilot, technical operators, and maintenance people of the NLF status in order to assure airworthiness, safety, and/or economic goals. This paper presents a methodology for the proposed HMS and the investigation results obtained to date.

2 Background

2.1 Factors Disrupting Laminar Flow

The chordwise percentage of laminar flow on the wing surface (laminarity) can be theoretically predicted and/or estimated given information about the airfoil, angle of attack, sweep angle, Reynolds number, and Mach number. For the real operational environment, there are many additional factors that can disrupt the laminar flow and prevent the achievement of this theoretical laminarity. Those factors include the following:[1,4,9,10]

1) *Flight conditions:* deviation of Mach number and/or Reynolds number, changes in pitch/ yaw/roll, and so forth;
2) *Surface conditions:* corrosion, repair patches, insect residuals, dirt, icing, and so forth;
3) *Manufacturing quality:* roughness, waviness, steps, gaps, and so forth;
4) *Atmospheric conditions:* atmospheric turbulence, rain drops, clouds, particulates such as ice crystals, and so forth;
5) *Engine noise and vibration.*

As one can easily see, an HMS is needed for NLF aircraft operations because there are many ways that the flow field over the wing can be affected (sources of uncertainty).

2.2 Health Monitoring and Management Systems Developed

Historically, health management is defined as 'the process of actively monitoring and managing vehicle sub-systems in the event of component failures'.[11] The sub-systems mainly refer to avionics and the engine. This concept has also been extended to the vehicle level, such as aircraft icing detection[12] and aircraft control augmentation.[13] At the vehicle level, the concern is not about failure of subsystems or components, but degradation of some aircraft performance parameter(s) that may result in degradation of control effectiveness or even to the degree of causing fatal accidents.

In all of these systems, although usually the term 'health' is not defined explicitly, one or several parameters is/are selected as the indicator(s), e.g. fan speed, exhaust gas temperature, and fuel flow rate for the engine health monitoring and management system. A review of existing health monitoring and management systems has shown that although they decompose their functions differently, the functions of almost all of these systems can be categorized into four general areas:[14]

1) *Monitoring:* data collection and analysis;
2) *Diagnosis:* fault detection and isolation;
3) *Prognosis:* trend/failure prediction and maintenance decision support information (such as remaining life estimation);
4) *Maintenance planning and actions*.

For a new health monitoring and management system, the function decomposition and site allocation (onboard/not onboard) should be determined based on considerations of contingency, urgency of action, impact severity, and so forth.

3 Proposed Methodology and Preliminary System Design

At the outset of this investigation the authors posed a series of key research questions that were used as guidelines for the overall development process. Summarized in Figure 1 they pertained to: the identification of possible NLF health indicators and metrics used to measure observed disturbances, the determination and selection of the specific aircraft sensors to be used, and finally formulation of the overall HMS algorithm and system to be designed.

3.1 Definition of 'Health' of an NLF Aircraft

Of the several meanings for the word 'health', the one which best suits our purpose is: 'the general condition of the body',[15] since we are interested in the status of (natural) laminar flow. Although it is desired that both the upper and lower surfaces of a wing have significant laminar flow, our initial design goal is to achieve high laminarity on the suction side since some devices installed on the lower surface, such as Krueger flaps, engine nacelles and maintenance access panels will make it difficult to achieve laminar flow. Therefore, the 'health' of an NLF aircraft is defined here as sustained, expected laminarity over the upper surface of a wing (or its complete and rapid recovery following a serious loss or deviation from its normal state).

3.2 Proposed NLF Aircraft Health Monitoring System

Since laminarity status information is needed for real-time flight management, an onboard/airborne HMS has to be incorporated in NLF aircraft. Considering other HMS in practice today and the special features of the problem at hand, the authors believe that the

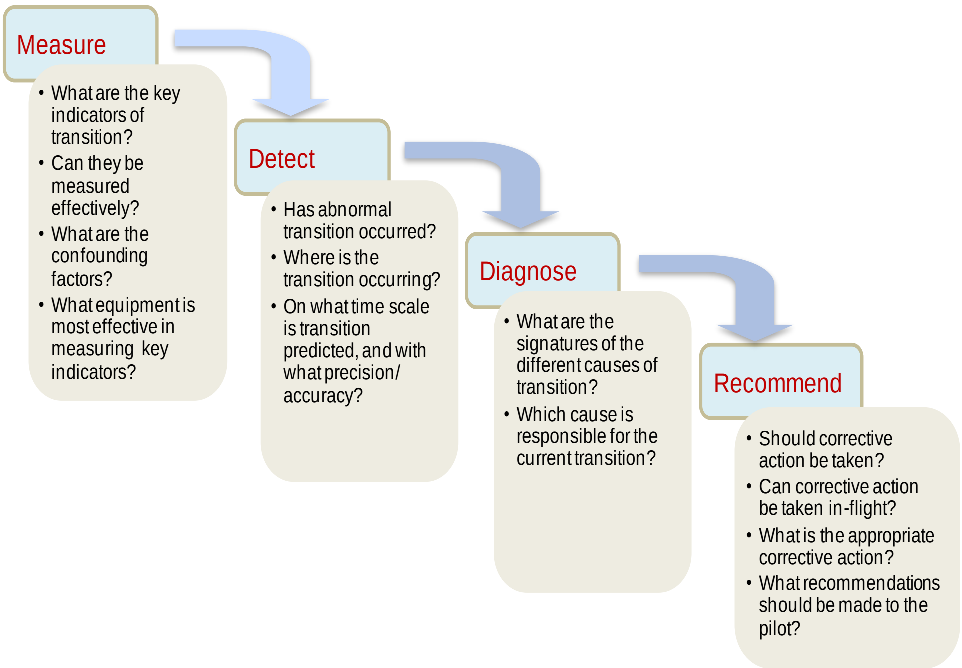

Figure 1. Key research questions posed to guide the development of the monitoring system.

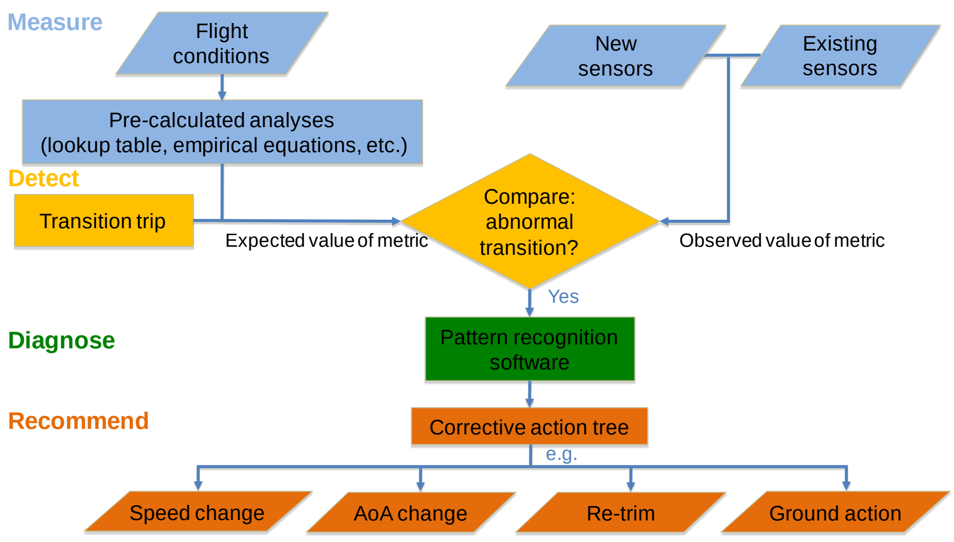

Figure 2. General logic flow of an NLF aircraft HMS

NLF aircraft monitoring system proposed should have the following four functions/modules:

1) *Measurement* of transition location and determination of aircraft performance characteristics;
2) *Detection* of abnormal transition during cruise;
3) *Diagnosis* of the cause of abnormal transition;
4) *Recommendations* for potential corrective actions.

The measurement and detection functions are envisioned to be performed in real-time continuously, while the diagnosis and recommendation functions are to be triggered only if an abnormal transition is detected. Figure 2 shows the general logic flow for such an NLF aircraft HMS.

The four-module system proposed above provides the system level functional decomposition and some general idea of the system architecture.

In this paper only the measurement and detection modules are investigated and discussed in detail, the remaining two modules will be addressed and documented as part of future work.

3.3 NLF Aircraft Health Indicators

For this study an indicator of NLF aircraft health must be able to detect upper surface laminarity. For this case two categories of indicators were formulated: flow field indicators and aircraft performance indicators.

Flow field based methods (FFBM) pertain to boundary layer properties, including temperature, total pressure, skin friction coefficient, speed, velocity direction/streamline pattern, acoustic noise frequency, and so forth, since they will all change at a given point of measurement when the transition front passes.[4]

Aircraft performance based methods (APBM) pertain to wing aerodynamic performance, including engine and stability and control parameters. Engine indicators include fuel flow rate, engine gas temperature (EGT), engine speeds (e.g., fan speed N1 and compressor speed N2 for turbojet aircraft; and shaft RPM for propeller aircraft). Since these all change with engine thrust, which is related to wing drag, it is hypothesized that they ought to be able to capture and quantify any laminarity changes experienced by the aircraft. Aircraft stability and control parameters are also considered since they can capture changes in wing lift, lift curve slope, wind directionality, moments, and so forth, which are also affected by wing laminarity changes.[7,8]

3.4 Monitor/ Measurement Module Concepts and Selection

Both flow-field based methods (FFBMs) and aircraft performance based methods (APBMs) are adopted for the monitor/measure module. Initially, one may think that only FFBM is needed, but in fact, the two methods are complementary because they are based on different mechanisms and provide different information and perspective in determining the condition of laminar flow. Moreover, the two methods are unlikely to fail simultaneously in providing information and can backup each other. In addition, aircraft performance data are needed for the diagnosis and recommendation modules. For example, it will be difficult for one to tell definitively, with only flow field data, the cause of laminar loss if the aircraft is flying too fast or too slow, or the angle of attack is too high.

3.4.1 Flow-field based methods (FFBMs)

FFBMs are used to determine laminarity either directly or after post-processing of the sensor data. They can be further classified as either global or local methods. With a global approach (e.g., IR camera), one has the capability to visualize the extent of laminar flow over the entire wing. Human eyes can recognize the transition front directly from IR images, but pattern recognition software will be needed for the computer to identify where the transition front is located.

Figure 3 illustrates the idea of IR camera placement and results for the global FFBM, with the blue regions laminar and the orange turbulent (including visible wedges).

With a local method (e.g. arrays of thermocouples), the sensor data need to be post-processed so as to determine the local state of the boundary layer. The response time and evaluation of the local method is anticipated to be much faster than for the global method, in other words, the thermocouples are expected to give a quick snapshot of the local state of the boundary layer. Figure 4 illustrates the insulated thermocouple sensor concept while Figure 5 (on the following page) shows a possible arrangement capable of detecting the presences of turbulent wedges and uniform transition.

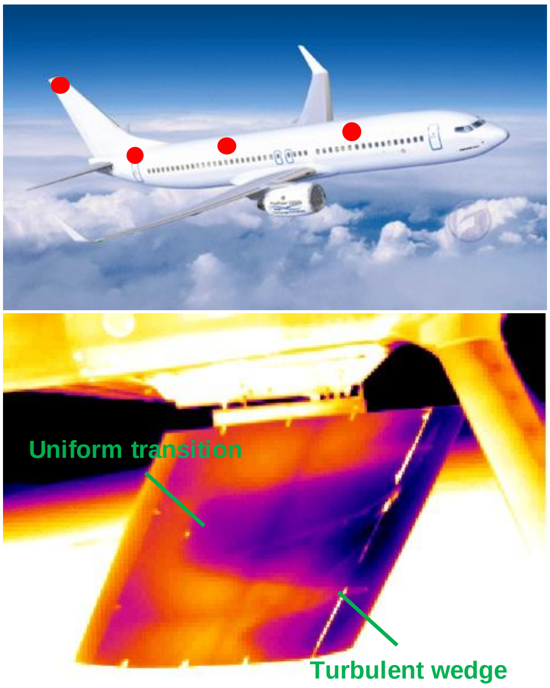

Figure 3. Possible installation of IR cameras (top) and a notional example of IR image (bottom; flow right to left)

The two methods are complementary and it is suggested that both approaches be implemented in an HMS and work hand-in-hand. The IR camera gives a full picture of the state of laminar flow but at a computational cost, while the thermocouples give a quick picture but require clever placement to accurately map a wide variety of off-design scenarios.

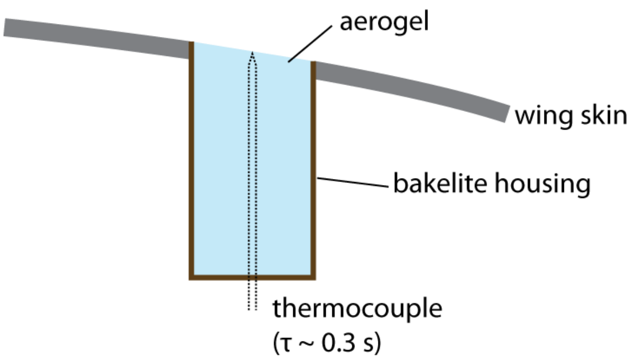

Figure 4. Insulated thermocouple sensor concept. The thermocouple is insulated from the wing skin in order to measure freestream adiabatic recovery temperature.

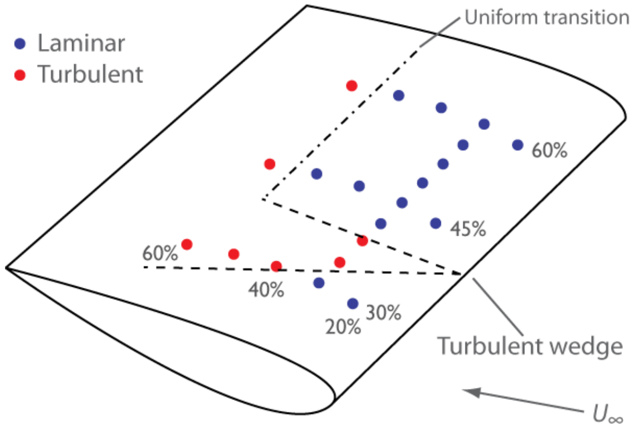

Figure 5. Possible installation of arrays of thermocouples (left) and installation of a single thermocouple (right).

The FFBMs considered in the selection analysis (described in the next section) are as follows:

Sensors with wired and wireless options (6×2=12): hotfilm anemometer, piezo-foil arrays, thermocouples, strain gauges, microphone array, laser-doppler velocimetery;

Sensors with wired-only option (10): stereoscopic particle image velocimeter, skin friction interferometer, sublimating chemicals, liquid crystals, infrared (IR) imaging, temperature sensitive paint, Preston tube, Fabry-Perot interferometer, wake rake, total pressure transducer.

3.4.2 Aircraft performance based methods (APBMs)

APBMs indirectly give an overall sense of the laminar flow, instead of details such as the location of the transition front. This kind of information is useful to trigger that a global disturbance has been detected possibly requiring further scrutiny by the FFBMs.

APBMs use fuel flow measurements and other aircraft sensors such as freestream temperature and pressure sensors, and engine speed sensors. All of the APBM sensors are current aircraft sensors, usually contained in the aircraft's FADEC (Full Authority Digital Electronic Control) system and thus no additional hardware costs are anticipated.

The data of these sensors are used to calculate the "performance distance", a new concept to be described next as the aircraft performance indicator.

3.5 Preliminary Design of Detection Module

The goal of the detection module is to detect abnormal transition or loss of laminarity. For FFBM, this can be done in a straightforward fashion by comparing real-time laminarity with reference laminarity. For APBM, this module will actually detect abnormal change of the selected aircraft performance indicator, then the diagnosis module will determine the cause. Here the focus is to develop the detection module based on the aircraft performance indicators, and the "performance distance difference (PDD)" is preferred. To eliminate effects of noise and insignificant transient changes in laminarity, the detection module adopts a probabilistic/statistical approach.

Kalman Filter (KF) based innovation methods[12] (as developed for ice detection) were considered for the detection module. See Figure 6 for the overall flowchart.

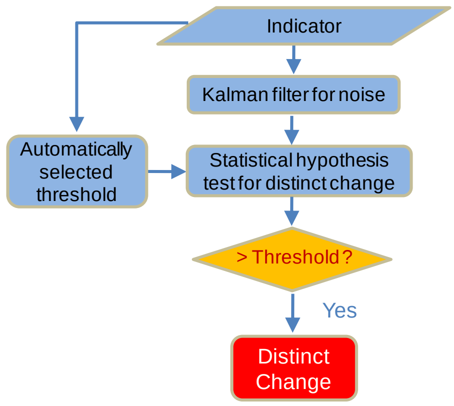

Figure 6. Overall logic flow for the detection module.

The parameter window length *W* is the number of points in the sampling pool. When the sampling rate is known, the window length corresponds to an observation time, which is required to determine if a detected change is in fact significant ("distinct change"). The window length can be adjusted by the user to reduce the number of false and/or missed alerts.

For example, if crosswind occurs and is large and sustained, the detection module will identify a distinct change of the performance indicator, and the diagnosis module can easily determine the cause based on aircraft heading and wind direction calculated. Otherwise, if it lasts over only a short time, the Kalman Filter will filter it out like noise.

3.6 FFBM sensor system selection methods (ISET and CSET)

3.6.1 Selection methodology

In order to assess the potential loss of laminar flow a set of suitable sensors will have to be identified and placed on the aircraft. For this reason a large set of sensors was investigated based on an extensive literature search and on subject-matter qualitative mappings of the findings against a set of suitable criteria. Based on this study, a multi-criteria decision-making tool (ISET, for individual sensors and CSET for sensor combinations) was formulated and created to assist in the down-selection of the most promising ones. To assist in this multi-criteria decision making exercise, a method was formulated based on TOPSIS (Technique for Order Preference by Similarity to Ideal Solution),[16] which is a very effective technique for making decisions/selections with limited qualitative and quantitative information. In order to account for the subjectivity of the information provided, a Monte Carlo Simulation (MCS) [17] was implemented to work with TOPSIS in order to assess the sensitivity of the outcomes to uncertainty associated with the provided inputs and to alleviate the effects of human bias in the decision process. Figure 7 on the following page shows the overall selection process.

The first step in using ISET is to assign a score in the range 1–9 (with 9 being the highest score) to each technology for various criteria, such as technology readiness level (TRL), [18] maintenance (the time scale required for upkeep of the technology), and effectiveness/resolution of a practical system (overall practicality of the system to determine occurrence, location, and source of flow transition or turbulent wedges in real-time, in-situ conditions). These scores were assigned based on a literature search for flight and wind-tunnel tests that used each sensor technology.

These scores are used in combination with weightings that determine the relative preference of each criterion, out of a total of 100%. The evaluation environment uses TOPSIS to calculate the distance from the ideal solution, and rank the technologies according to their overall score. An overview of the basic analysis user interface is shown in Figure 8 on the previous page. The components of this interface will be described by walking through components shown.

Figure 9 allows the user to assign weights to each criterion individually, or to activate a set of predefined weights. For example, the user may desire the short-term solution that would focus on a high TRL for immediate implementation, or the cost-oriented solution that would value the sensor technology with the lowest overall system cost.

Figure 10 shows the consumer report, a summary of the scores (ranging from 1–9, with 9 being the best) assigned all of the attributes for each technology. For instance, IR thermography received a 6 for TRL: its ability to be used to detect transition has been demonstrated in a relevant flight environment[19], but a complete system has not been used in a operational laminar-flow transport aircraft environment.

An additional control is provided here to set a minimum threshold that would flag (in red) sensors that violate this threshold. These sensors can then easily be eliminated from further analysis, if the customer did not want to evaluate any technology in violation. For example, in Figure 10, a minimum TRL of 3 is applied and it is clear to see the technologies with too-low TRL.

The ranking results are shown Figure 11. Sensors that violate a specified threshold in the consumer report are flagged in red, while the deviation of the ranking from default (equal weights) is shown at the right. The chart at the bottom shows the relative scores, where 1.0 is the theoretical optimum.

Finally, Figure 12 shows a radar graph of weighted scores compared to customer preferences.

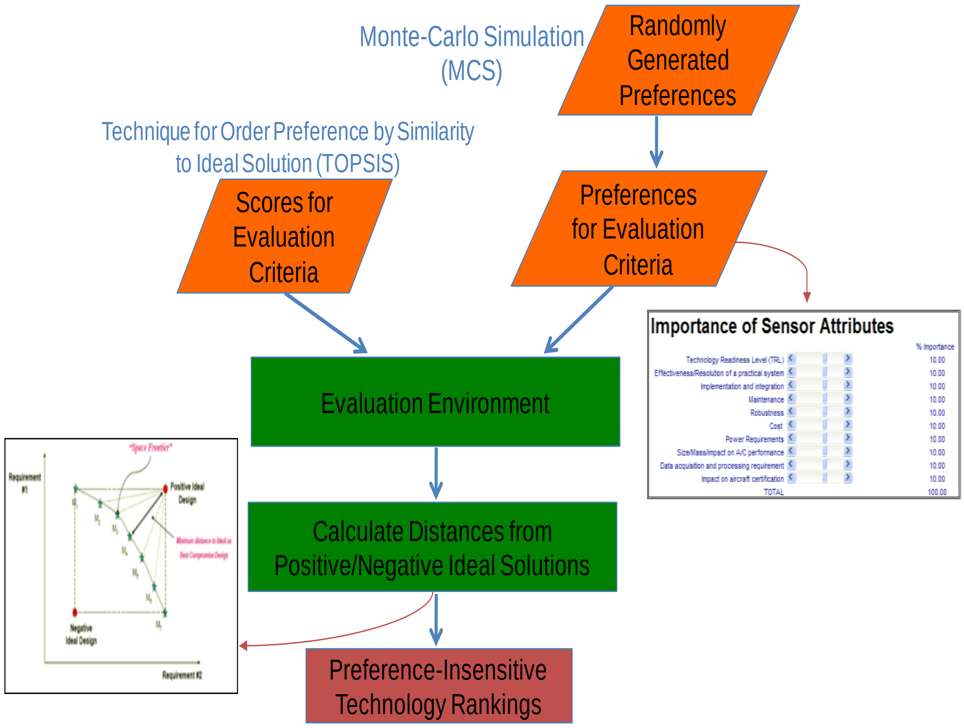

Figure 7. Overall methodology for the sensor selection.

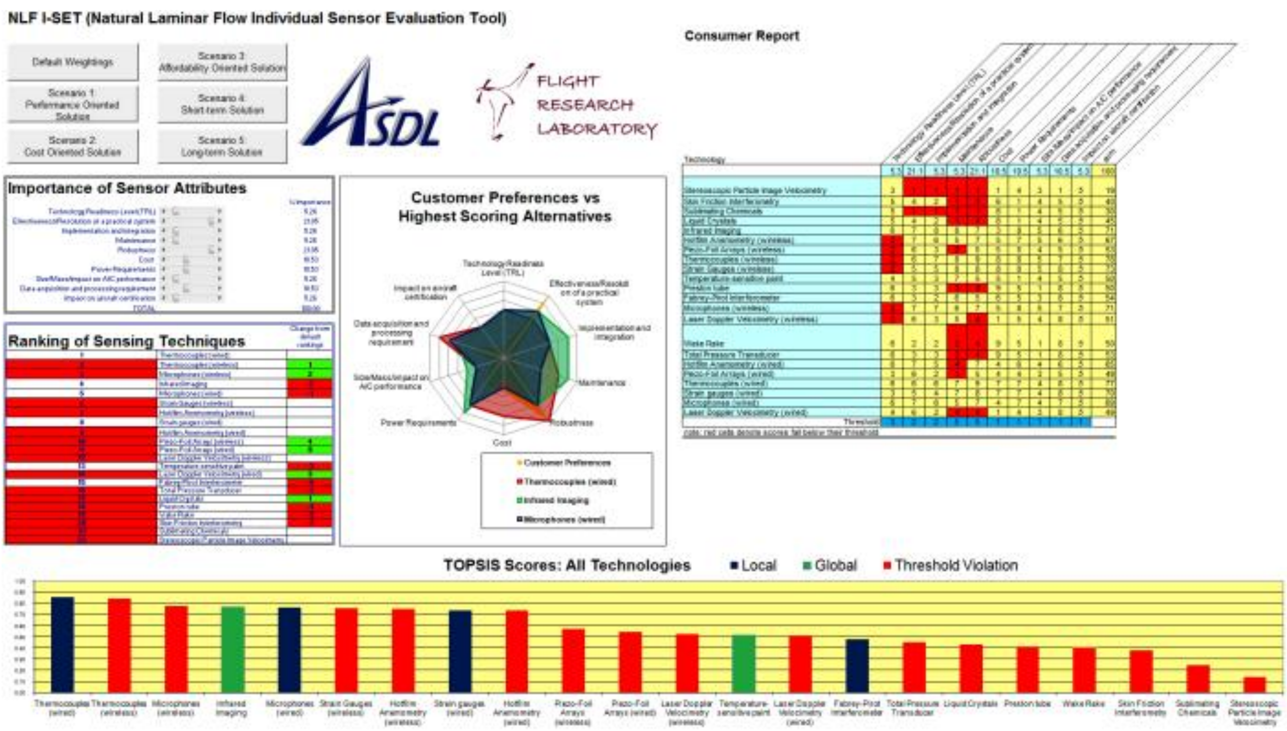

Figure 8. ISET reporting interface overview.

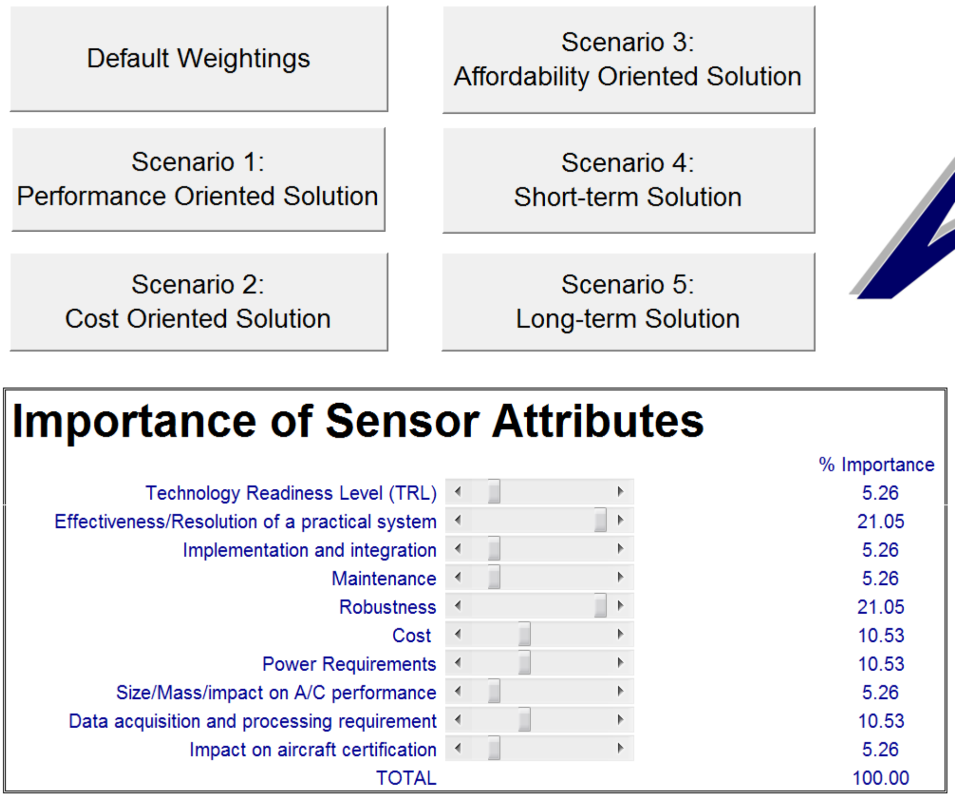

Figure 9. Attribute weighting specification interface.

Consumer Report

Technology	Technology Readiness Level (TRL)	Effectiveness/Resolution of a practical system	Implementation and integration	Maintenance	Robustness	Cost	Power Requirements	Size/Mass/impact on A/C performance	Data acquisition and processing requirement	Impact on aircraft certification	sum
	5.3	21.1	5.3	5.3	21.1	10.5	10.5	5.3	10.5	5.3	100
Stereoscopic Particle Image Velocimetry	3	1	1	1	1	1	4	3	1	5	19
Skin Friction Interferometry	5	4	2	1	3	6	1	4	5	5	40
Sublimating Chemicals	5	1	1	1	1	8	1	4	5	5	30
Liquid Crystals	5	4	2	1	4	8	1	4	5	5	45
Infrared Imaging	6	7	8	8	7	3	8	5	6	5	71
Hotfilm Anemometry (wireless)	2	7	6	5	7	5	7	5	6	5	67
Piezo-Foil Arrays (wireless)	2	6	3	2	5	5	5	4	5	5	53
Thermocouples (wireless)	2	6	7	8	9	8	8	5	7	5	78
Strain Gauges (wireless)	2	5	5	8	8	8	8	5	8	5	73
Temperature-sensitive paint	4	5	3	7	5	5	1	4	5	5	50
Preston tube	6	3	3	3	3	9	5	1	8	5	50
Fabrey-Pirot Interferometer	6	3	2	6	5	6	5	3	8	5	54
Microphones (wireless)	2	7	7	6	7	5	8	5	7	5	71
Laser Doppler Velocimetry (wireless)	2	6	3	5	4	1	5	4	8	5	51
Wake Rake	6	2	2	3	4	9	5	1	8	5	50
Total Pressure Transducer	6	3	3	3	4	9	5	1	8	5	53
Hotfilm Anemometry (wired)	6	7	5	4	7	4	6	4	6	5	65
Piezo-Foil Arrays (wired)	3	6	2	1	5	4	4	3	5	5	49
Thermocouples (wired)	6	6	6	7	9	7	7	4	8	5	77
Strain gauges (wired)	3	5	4	7	8	7	7	4	8	5	70
Microphones (wired)	6	7	6	5	7	4	7	4	7	5	69
Laser Doppler Velocimetry (wired)	4	6	2	4	4	1	4	3	8	5	49
Threshold	3	2	2	5	5	1	1	1	1	1	

note: red cells denote scores fall below their threshold

Figure 10. Example consumer evaluation report using TOPSIS for sensor selection.

Ranking of Sensing Techniques		Change from default rankings
1	Thermocouples (wired)	
2	Thermocouples (wireless)	1
3	Microphones (wireless)	2
4	Infrared Imaging	-2
5	Microphones (wired)	-1
6	Strain Gauges (wireless)	
7	Hotfilm Anemometry (wireless)	
8	Strain gauges (wired)	
9	Hotfilm Anemometry (wired)	
10	Piezo-Foil Arrays (wireless)	4
11	Piezo-Foil Arrays (wired)	9
12	Laser Doppler Velocimetry (wireless)	
13	Temperature-sensitive paint	-3
14	Laser Doppler Velocimetry (wired)	3
15	Fabrey-Pirot Interferometer	-4
16	Total Pressure Transducer	-3
17	Liquid Crystals	1
18	Preston tube	-3
19	Wake Rake	-3
20	Skin Friction Interferometry	-1
21	Sublimating Chemicals	
22	Stereoscopic Particle Image Velocimetry	

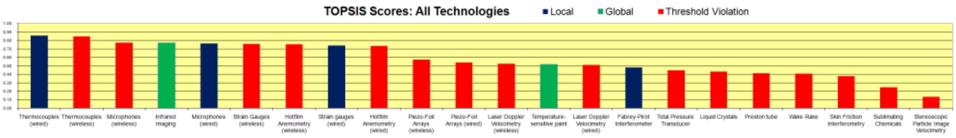

Figure 11. Sensor ranking results.

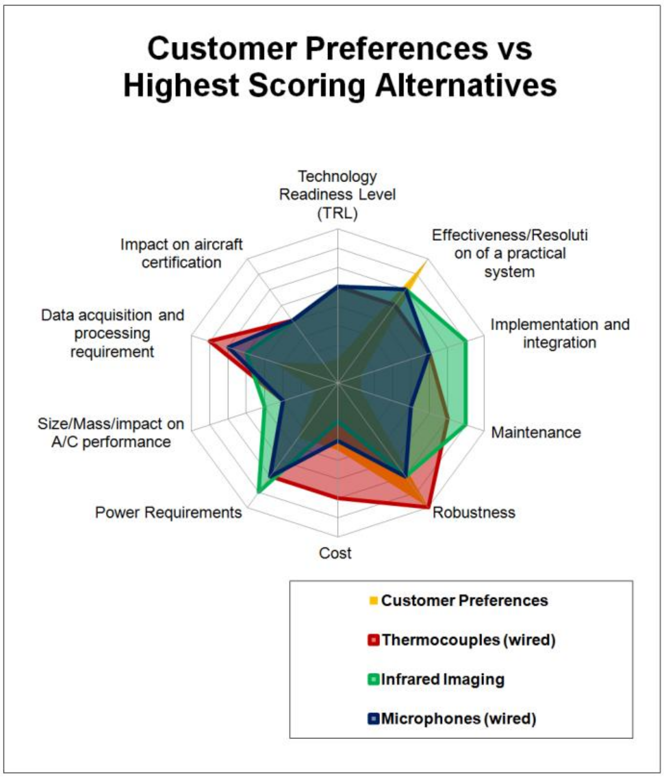

Figure 12. Radar graph of consumer evaluation scores for top three technologies.

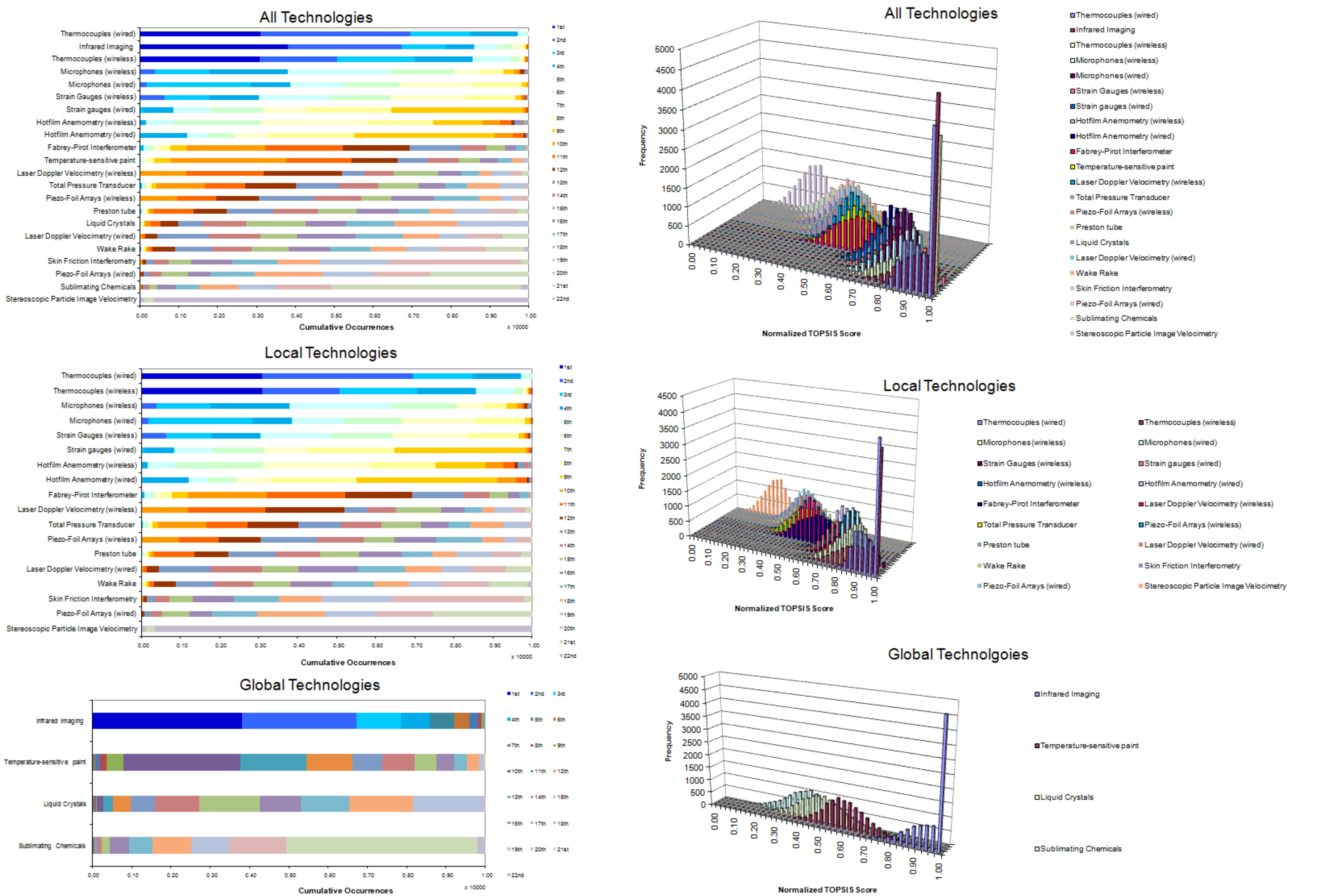

Figure 13. MCS results for criteria weighing sensitivity analysis.

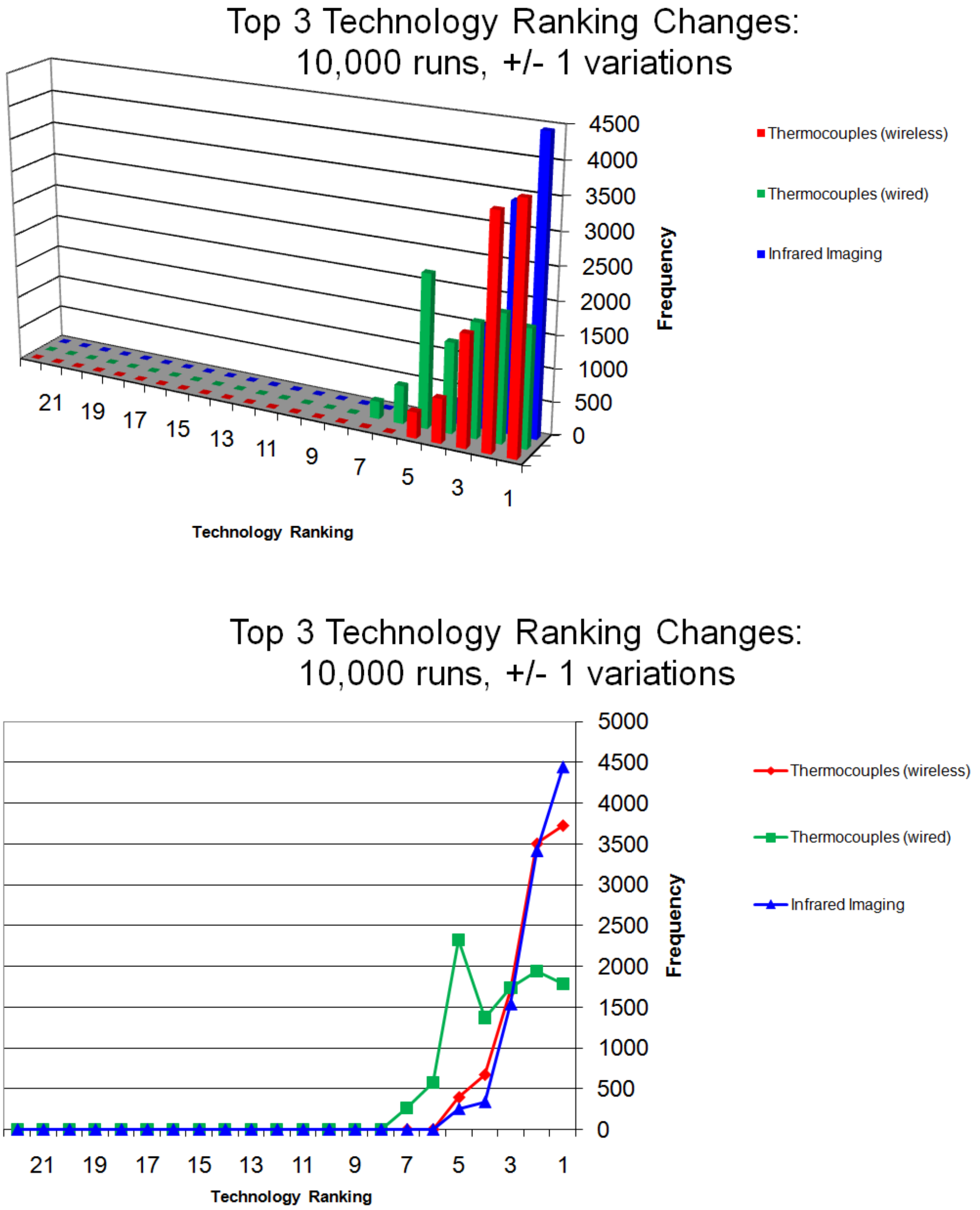

Figure 14. MCS results for score input sensitivity analysis.

Two MCS methods are employed in ISET for sensitivity analysis. The first, shown in Figure 13, verifies the sensitivity of the solution to variations in weighting inputs. The MCS varies the weights, and counts the number of times a particular technology places in a particular rank. The second MCS, Figure 14, varies the input attribute scorings by ±1 and counts the results.

3.6.2 Selection criteria

There are ten selection criteria employed in the selection tool. These criteria, along with definitions and evaluation scale (from 1–9, 9 being the highest), are as follows.

1) *Technology readiness level:* A measure of the maturity of the technology with respect to its ability to be utilized in flight. The low and high values on the scale correspond to the following: 1, Basic principles observed and reported; 9, Technology has been proven in successful mission operations.[18]
2) *Effectiveness and resolution of a practical system*: Ability of a practically implementable system to determine occurrence, location, and source of flow transition (e.g. turbulent wedges) in real-time, in situ conditions. Scale: 1, unable to provide real-time or in-situ information; 9, provides complete and accurate real-time, in situ information, including number and location of turbulent wedges present.
3) *Implementation and integration requirements:* Overall practicality of the solution in terms of its application to a commercial aircraft, specifically with respect to required equipment.
4) *Maintenance:* Time scale of required upkeep of the technology. Scale: 1, every flight; 9, once every seven years.
5) *Robustness:* Ability of the technology to sustain measurements, survive the extremes of flight conditions (temperatures, precipitation, and turbulence), and sensor redundancy.
6) *Cost:* Investment needed to outfit an aircraft with the technology including the sensor(s) and all other avionics necessary. Scale: 1, 0.5% of aircraft acquisition cost; 9, 0% of aircraft acquisition cost.
7) *Power requirements:* Power levels and distribution required to run the sensors and all other onboard analysis tools necessary to arrive at a diagnosis. Scale: 1, 3 kW; 9, 0 kW.
8) *Size/mass/impact on aircraft performance*: Size/mass of the sensor and all other onboard analysis tools necessary to arrive at a diagnosis. Scale: 1, 50 kg; 9, 0 kg.
9) *Data acquisition and processing requirements:* Comparison of the data acquisition rate (bandwidth) and processing requirements for the sensor, compatibility with AFDX bus.
10) *Impact on aircraft certification:* Does implementation of the technology result in a more time intensive or costly certification process? 1: uncertifiable; 9: no impact.

3.6.3 Selection results

Both as individual sensors and for use in combination and in arrays, the top 2 candidates were determined to be the wired thermocouples and the IR camera. Both sensors require installation on the aircraft. Wireless technology, although attractive, was determined to be of a too-low TRL and did not warrant further consideration. Both technologies were robust to variations in customer preferences (weightings) and attribute scorings.

For the aircraft performance sensors, the initial selection converged on sensors already found on today’s aircraft and their FADEC systems. These include sensors such as the fuel flow meter, free stream temperature and pressure sensors, inertia reference unit, control surface location sensors, and so forth, and thus no selection exercise was needed.

3.7 Concept of performance distance

At the beginning of this research, fuel flow rate (FFR) from fuel flow meters via the engine FADEC device was considered as the aircraft performance indicator. However, the investigation revealed that it was very hard to tell the exact cause for any changes observed in FFR. Critical factors included degradation of engine performance and degradation of airframe aerodynamic performance with operational time,[20] and effects of crosswinds.

Another important issue is that the engine performance changes with flight conditions (speed, air temperature, air density, and so forth), and thus higher FFR at one flight condition does not necessarily mean abnormal loss of laminar flow, as is the case when the aircraft flies from a cold air zone to a warm one.

All of the issues above forced the research team to find a new robust aircraft performance indicator. Called "performance distance", this indicator is defined/calculated as follows:

$$\text{Performance distance} = (\text{Real performance} - \text{reference performance}) / \text{reference performance} \quad (1)$$

Here performance can be any of the aircraft performance indicators discussed previously, for example, FFR, N1, and so forth. Real performance means the data obtained in real time. Reference performance means the data obtained with an aircraft (a specific combination of airframe and engines) that is new or has just entered into service; in other words, this aircraft has no engine performance degradation or airframe aerodynamic performance degradation. Reference performance data should be obtained for different Mach numbers, (pressure) altitudes, and real air (ISA and non-ISA temperatures). Note that the real performance data will never be better than the reference performance data.

The performance distance values should be about the same for aircraft with the same weight and engine type (turbojet, reciprocal engine + propeller, and so forth) even at different flight conditions (Mach number, altitudes, air temperatures, and so forth). This claim is based on the fact that, if the real performance data are obtained with a new aircraft, the performance distance is zero at any flight conditions.

3.8 Boundary layer trips for calibration and performance distance difference

The concept of performance distance enables fair comparison of aircraft performance at different flight conditions. Additional information and a calibration of the system can be achieved by the inclusion of a leading-edge boundary-layer trip device. Fixed at about the 5% x/c chordwise location and tunable in flight to be actuated in different prescribed spanwise patterns, the trip provides a real comparison among laminar and various known turbulent conditions, and isolates the effects of turbulent flow alone. One proposal for the trip is to use Shape Memory Alloys (SMA).

In one application, the trip device will be activated at the beginning of cruise to simulate a completely turbulent wing, and the corresponding calculated performance distance will be the termed the "maximum performance distance (MPD)". Once turned off, "real-time performance distance (RPD)" will be calculated for the remainder of the flight. The "performance distance difference (PDD)" is then defined/calculated as follows:

$$\text{PDD} = \text{maximum performance distance} - \text{real-time performance distance} \quad (2)$$

One can easily see that the effects of engine performance degradation and airframe aerodynamic performance degradation (not directly related to a loss in laminar flow) are canceled out in PDD. It is the PDD data that are sent to the detection module as the final aircraft performance indicator.

PDD will become smaller with loss of laminar flow. If the area-averaged laminarity of the reference aircraft at a given flight condition is known in advance, then the real-time area-averaged laminarity is estimated as follows:

$$\text{Real-time laminarity} = \text{PDD} / \text{MPD} \times \text{reference laminarity} \quad (3)$$

4 Some Thoughts about the Diagnosis and Recommendation Modules

The diagnosis module is envisioned to use an ‘if-then’ inference engine. It must differentiate intended changes caused by the pilot or autoflight system from unintended ones caused by abnormal transition. This can be done by checking the history of engine throttle setting, flight control surface position settings, wind aloft conditions, and so forth. It also needs to check the history of the FFR at self-calibration in order to identify the cases of bug residuals, which usually happen at low altitudes.

The recommendation module will include a fast function to estimate the remaining range potential. Corrective action recommendations should be given based on the cause of abnormal transition and remaining range estimate. It should give actions different urgency, such as in-flight action, line inspection, after flight maintenance, and so forth.

5 Conclusions and Summary

Maintaining laminar flow on the wings, empennage, and parts of the fuselage is the most promising technology for reducing the overall drag on a flight vehicle. For laminar flow control to be successful and accepted, the community has recognized that a Health Monitoring System (HMS) has to be an integral part of the system. An HMS should have the following functions/modules: measurement, detection, diagnosis, and recommendation. The first two are detailed here, with some thoughts on the latter two for future work.

Because the ability to maintain laminar flow depends on numerous factors, in this work is proposed a methodology combining real-time information about the boundary-layer flow and aircraft performance to monitor the state of the expected laminar flow on a wing. A powerful multi-criteria decision-making tool was formulated and created to assist in the down-selection of the most promising sensors and combinations thereof for the flow field based methods. Selection criteria and priority weightings were determined through much thoughtful discussion among the team members. A Monte Carlo Simulation was implemented to assess the sensitivity of the outcomes to uncertainty in scores subjectively assigned, and showed the top-ranked results to be relatively insensitive to variations in attribute score assignments and weights. These uniformly top-ranked sensors were wired thermocouples and IR thermography, and recommendations for implementation proposed.

Related to aircraft performance, initial selection converged on sensors already found on today’s aircraft and their FADEC systems. The performance distance concept is introduced to evaluate aircraft performance measures. Additional information and a calibration of the system can be achieved by the inclusion of a leading-edge boundary-layer trip device.

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