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CERTIFICATION ASPECTS OF AIRPLANES WHICH MAY OPERATE WITH SIGNIFICANT NATURAL LAMINAR FLOW

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INTRODUCTION

Recent research by NASA indicates that extensive natural laminar flow (NLF) is attainable on modern high performance airplanes currently under development. Modern airframe construction methods and materials, such as milled aluminum skins, bonded aluminum skins, and composite materials, offer the potential for production aerodynamic surfaces having waviness and roughness below the values which are critical for boundary layer transition. In addition, the current trend is to higher wing loadings, higher aspect ratios, and higher cruise altitudes, all of which produce lower chord Reynolds numbers and, therefore, the possibility for more extensive laminar flow. We also expect to see an increasing application of modern computer designed airfoils which can be tailored to promote more extensive NLF.

The purpose of this paper is to identify areas of concern with the certification aspects of NLF and to stimulate thought and discussion of the possible problems at an early date. During its development, consideration has been given to the recent research information available on several small business and experimental airplanes and the certification and operating rules for general aviation airplanes. The certification considerations discussed are generally applicable to both large and small airplanes. However, from the information available at this time, we expect more extensive NLF on small airplanes because of their lower operating Reynolds numbers and cleaner leading edges (due to lack of leading-edge high lift devices). Further, the employment of composite materials for aerodynamic surfaces, which will permit incorporation of NLF technology, is currently beginning to appear in small airplanes.

The Certification Process

When a new airplane employing advanced technology is being developed, the FAA should be advised at the earliest possible time. This will permit an early identification of the certification issues and, if required, the timely development of any special conditions which may be necessary to provide a level of safety equivalent to that established in the regulations. Under the provision of the Federal Aviation Regulations (FAR) Part 21, Certification Procedures for Products and Parts, section 21.16, special conditions (SC) may be imposed when the applicable airworthiness regulations do not contain adequate or appropriate standards because of a novel or unusual design feature. These imposed SC become part of the airplane tape certification basis. The airworthiness regulations are updated and amended at intervals, with public participation, to cover recent aeronautical progress and thereby preclude the need for special conditions in subsequent airplane type certification projects.

General Concerns

The general concern in certification of airplanes having extensive NLF is that the extent of laminar flow may change during the airplane's operation, because of surface contamination due to: an accumulation of insects or dirt, condensation or rain, and frost or ice. Also, the original surface quality, as certificated, may change because of minor service damage, paint chipping or peeling, or changes in paint schemes or paint application techniques. Since extensive NLF is attainable, but not assured, consideration must be given to the effects of loss of a significant portion of laminar flow.

The following trends have been observed on airfoil sections where extensive NLF is possible:

- The upper and lower surface local pressures may be significantly different for natural transition than when the transition point is fixed close to the leading edge.
- The lift curve slope may be higher.
- The pitching moment coefficient may be more positive.
- The drag is normally lower at cruise angle of attack.

Loss of NLF may result in adverse changes in performance (including stall speed, rate of climb, and range), flying qualities, and airloads. If significant NLF is expected to be attainable, the applicant should present information early in the certification process on the possible extent of NLF, how maintenance of NLF will be assured, and the consequences of the loss of a significant portion of NLF. Verification by test will likely be necessary. Flight testing techniques, such as the use of sublimation chemicals to determine the extent of NLF, and artificial means to force boundary layer transition may be required. Wind tunnel testing done at much lower than normal flight Reynolds numbers will likely not be accepted.

PERFORMANCE

Stall Speed (FAR Part 23 - Airworthiness Standards; Normal, Utility and Acrobatic Category Airplanes - section 23.49)

For airfoils having appreciable NLF, the maximum lift may be adversely affected by loss of laminar flow with a corresponding increase in stall speed. However, this depends on the sensitivity of the airfoil and whether flow separation is involved. For a single engine composite structure airplane with an NACA 63_2-215 airfoil, test data provided in Reference 1, the maximum lift coefficient actually increased about 4 percent when boundary layer transition was fixed at 5 percent chord. However, other research has shown a reduction of maximum lift on airfoils designed for maintaining a laminar boundary layer, when transition was fixed near the leading edge (Reference 2).

Loss of NLF on a canard or tandem wing airplane may have severe adverse aerodynamic effects. This was shown in the tests of both canard configured airplanes reported in Reference 1. For the more severe case, fixed transition on the wings, winglets, and nose caused an 11 knot increase in minimum trim speed, corresponding to a 27 percent decrease in maximum lift.

The current certification regulations applicable to single-engine airplanes and to multiengine airplanes of 6,000 pounds or less maximum weight which do not have one-engine inoperative climb performance require a stall speed of 61 knots or less with the airplane in the landing configuration at maximum weight. For an NLF airplane of this type that may have a stall speed close to the 61 knot limit, an increase in stall speed due to loss of NLF may result in the design not being able to comply with this requirement.

Takeoff and Landing (FAR sections 23.51 and 23.75)

These sections of the FAR require the landing approach speed and the climb speed attained at the end of the takeoff distance (50 foot height) to be 30 percent greater than the stall speeds in the takeoff and landing configurations, respectively. If the stall speed increases because of loss of NLF, the takeoff and landing distances will also increase. If flight planning does not allow for this possibility, an intended destination runway may be too short for a safe landing.

Climb (FAR sections 23.65, 23.67 and 23.77)

A loss of NLF could result in a significant drag increase and may result in a lift curve slope decrease. Thus, the lift to drag ratio and the rate of climb could decrease. Section 23.67 contains one-engine inoperative climb requirements which are related to stall speed squared. Therefore, if a loss of NLF causes the stall speed to increase, the minimum rate of climb required will increase, with the possibility that this requirement will not be met.

FLIGHT CHARACTERISTICS

From review of the results of NASA research reported in References 1 and 3, it does not appear that testing of conventional configured airplanes included an evaluation of the effects of the loss of NLF on stability and control. The FAA would be concerned about how NLF and its loss change these parameters.

For the two canard configured airplanes tested in References 1 and 3, significant effects on longitudinal handling qualities were found when extensive NLF was changed to turbulent flow by fixing transition near the leading edge on both lifting surfaces. Full scale wind tunnel tests show a large increase in the trim elevator deflections required at any airspeed, a 7 to 11 knot increase in minimum trim speed, and some reduction in short period damping at cruise speed. These changes were attributed to loss of lift on the forward surface caused by turbulent flow separation near the trailing edge when NLF was lost. The forward wing was designed for a laminar boundary layer with attached flow. Loss of NLF and loss of forward wing lift also occurred with water sprayed on the wings to simulate rain during wind tunnel testing. These effects of fixed transition on the lifting surfaces (resulting in loss of NLF) were also seen in flight testing the canard configured airplanes reported in Reference 1.

Part 23 of the FAR contains the certification standards for controllability and maneuverability in sections 23.143 to 23.157, for trim in section 23.161, and for stability in sections 23.171 to 23.181. Loss of NLF may have a significant or even critical effect on the airplane's ability to meet these standards. A significant change in airfoil pressure distribution and moment coefficient due to loss of NLF could change the stabilizing and control forces which must be provided by the horizontal tail. Such a change would be evaluated to determine that the current standards and criteria are met for longitudinal control, control during landings, elevator control force in maneuvers, trim, static longitudinal stability, and dynamic stability.

Lateral handling characteristics may be adversely affected by asymmetric loss of NLF on a wing using an airfoil section which is sensitive to surface roughness and waviness. This could be a particular problem if the construction methods, skin thickness, etc., are not adequate to ensure that both right and left wing panels are within the tolerances required for maintenance of NLF. It is possible that such critical variations may not be present in the certification test airplane but may appear later on production airplanes and could become a problem on in-service airplanes if both wings are not maintained to the same standards.

For conventional airplane configurations, a loss of NLF on the wings would not be expected to have significant effects on the directional handling characteristics, unless it were an asymmetric loss, as discussed above, which would cause a spanwise asymmetric distribution of drag. However, a change of boundary layer state and possible associated flow separation on the vertical tail, due to high yaw angles or contaminated surface condition, could result in significant changes in directional stability and control and a higher minimum control speed (for multiengine airplanes). Canard or tandem wing configurations having winglets which obtain significant NLF and which also serve as the vertical tail surfaces pose a more difficult design problem in this respect because the winglets are normally cambered and set at an angle of incidence (with respect to the airplane centerline) to minimize the wing induced drag.

Stall and spin certification standards are contained in FAR sections 23.201 to 23.221. Airfoil section aerodynamic characteristics are known to directly affect stall and spin characteristics. The shape of the lift curve top (C_l versus α) is one of the most important design considerations for low-speed flight because it directly reflects the potential seriousness of the stall-spin characteristics of the airplane (Reference 4). A sharp lift curve top where lift decreases rapidly with angle of attack (due to large areas of flow separation) usually results in a large bank angle (roll-off) at stall. Laminar flow airfoil sections usually have a favorable shape of the lift curve top because flow separation normally starts at the trailing edge. However, cases of leading edge flow separation stalls have been observed on laminar flow airfoils which have been improperly designed.

It should be shown by flight test with fixed transition that loss of NLF will not affect the stall and spin recovery characteristics to the extent that the applicable certification FAR sections will not be met. For a laminar flow wing, the importance of limiting differences in right and left lifting surface panels due to manufacturing tolerances for airfoil contour, skin waviness, and roughness should be emphasized. An asymmetric loss of NLF may have an adverse effect on lateral handling characteristics at stall, and possibly on spin recovery. For wings having significant NLF, it will be necessary to investigate the likelihood or effects of asymmetric loss of laminar flow on stall and spin recovery characteristics.

FLIGHT LOADS

Certification standards for flight loads including control surface and tail surface loads are contained in Part 23 of the FAR, sections 23.321 through 23.459. As discussed in previous paragraphs, the boundary layer state, i.e., laminar or turbulent, may have a significant effect on the airfoil pressure distribution, lift curve slope, moment coefficient, and profile drag. Buckling or distortion of airfoil skins under maneuver or gust loading may cause a change in the boundary layer state. These factors will affect the distribution of air loads chordwise and possibly spanwise (symmetric and asymmetric), the gust loads, and the balancing tail loads. The extent of NLF is dependent on the surface condition and accuracy of the airfoil contours which, in turn, are dependent on factors in design, manufacture, maintenance, and operations.

During certification, the applicant should present type design data showing the extent of NLF expected, the likelihood of loss of NLF, the extent of NLF loss that may occur, and the maintenance necessary to assure that NLF is retained. Structural design flight loads should include the extremes defined by natural transition and by fixed transition near the leading edge. Flight testing using a technique such as the use of sublimating chemicals to determine the extent of NLF and artificial means to cause boundary layer transition may be required.

FLUTTER

FAR section 23.629 requires that the airplane be free from flutter, control reversal, and divergence. The FAA is not aware of any research that has indicated that a changing boundary layer may result in a flutter problem. However, this is an area that should be researched to determine the potential for flutter problems or to alleviate concerns about such problems arising. Two possible factors to consider are as follows:

(a) The effect of a changing pressure distribution on wing torsion loads and hence elastic wing twist.

(b) Pressure loadings on control surfaces can change significantly with change in boundary layer state, particularly if trailing edge separation occurs.

RANGE

For several airplanes tested in Reference 1, an increase of about 25 percent in cruise drag was measured due to loss of laminar flow caused by artificially fixing boundary layer transition near the leading edge. This drag increase would result in a 20 percent loss of range according to the Breguet Range Formula, assuming the propeller efficiency and power setting are unchanged. If flight planning is based on the range which can be achieved with full laminar flow existing, then adequate cautions and cruise performance information should be provided to the pilot in the event laminar flow is lost or only partially existing, due to surface contamination (insects, moisture, dirt, ice, etc.).

It would be desirable to provide the pilot with direct information on the boundary layer state. A simple boundary layer state indicator is now available for gliders. This system includes a total pressure averaging rake which is mounted at the trailing edge of the wing. When the boundary layer flow is laminar, the total pressure ports of the rake are outside the boundary layer and sense essentially free stream total pressure. When the flow is turbulent, the rake is immersed in the thickened boundary layer and senses a much lower average total pressure. The rake is connected by a single tube to a pressure indicator on the instrument panel which is referenced to the airspeed system total pressure. This provides a direct reading to the pilot on boundary layer state.

There are no present requirements for providing range performance data in the FAA approved flight manual. This information is normally provided by the airplane manufacturer in the Pilot's Operating Handbook. The pilot uses the cruise performance information to determine the fuel requirements for a particular flight. Because of the possible range differences that may be realized due to the boundary layer being either laminar or turbulent, special conditions may be needed in the type certification basis to provide a level of safety equivalent to that established in the regulations.

FAA operating regulations regarding fuel requirements for General Aviation are contained in FAR Part 91, General Operating and Flight Rules (sections 91.22 and 91.23); for Air Taxi and Commercial Operators in FAR Part 135 (sections 135.209, 135.217, and 135.233); and for Domestic and Flag Air Carriers in FAR Part 121.

PROPELLERS

In Reference 1, considerable laminar flow was shown to exist on a metal propeller operating at a Reynolds number of about 1.5 million at the 50 percent blade radius (2700 RPM, CAS = 133 kts, advance ratio = .84). For radial stations between 25 and 75 percent radius, the transition location on the forward face of the propeller blade was at 38 percent chord and 80 percent chord on the aft face.

FAR section 23.33 contains standards for propeller speed and pitch limits for fixed pitch, controllable pitch, and constant speed propellers. The blade element drag (which determines torque required) can change as a function of the amount of NLF being achieved. The changing surface roughness of propellers, due to nicks, pitting, insects, etc., would have an effect on the NLF achieved, particularly on propellers designed to use laminar flow airfoil sections. The resulting change in blade element drag could be substantial, thus affecting the relationship between propeller pitch and engine RPM.

FAR section 23.45 requires that performance testing be accomplished with the approved power, less installation and accessory losses. For reasons discussed above, the relationship of thrust and power setting for a propeller may vary depending on the amount of NLF existing. This would likely be an important consideration if the propeller was specifically designed to achieve large amounts of NLF.

ICE PROTECTION AND DEICING EQUIPMENT

FAR sections 23.1416 and 23.1419 contain standards for deicing and ice protection systems. The existence of NLF has no effect on the performance of these systems. However, icing equipment is sometimes added (by a Supplemental Type Certificate approval) after an airplane has been type certificated. For an airplane designed to achieve significant NLF, addition of deicing boots, fluid outlets, etc., could produce changes in the boundary layer that could dramatically change the vehicle's performance, flying qualities, and aerodynamic loads.

Porous-fluid-exuding leading edges have been studied (Reference 3) as a means of providing protection against both ice and insect contamination which may trip the laminar boundary layer. Such equipment would have to comply with FAR section 23.1419 for ice protection systems, and in addition, there may be reliability considerations in its use for maintaining a laminar boundary layer.

FLIGHT MANUAL

The airplane flight manual contains information necessary for safe operation of the airplane as required by FAR sections 23.1581 through 23.1589. The performance effects of NLF (including loss of NLF), which were discussed earlier, will need to be reflected in the flight manual material as follows:

(a) Recommended climb speed.

(b) Approach speeds.

(c) One engine inoperative procedures including minimum control speeds, landing and go around with one engine inoperative, and effects of airplane configuration.

(d) Stalling speeds for the clean configuration and for landing gear and flaps down.

(e) Takeoff distance.

(f) Landing distance.

(g) Rate of climb or climb gradient.

DESIGN AND CONSTRUCTION

Previously we noted that modern airframe construction methods and materials, such as milled aluminum skins, bonded aluminum skins, and composite materials, offer the potential for production aerodynamic surfaces having waviness and roughness below the values which are critical for boundary layer transition.

Conversely, a decision to reduce airframe drag by employing NLF will likely influence structural design, e.g., rib spacing, stiffer skins, and elimination of skin laps.

Since airplane performance, flying qualities, and flight loads may change significantly with boundary layer state, the fabrication methods used to manufacture each production article on an airplane designed for extensive laminar flow may be considered a critical process. An example of a possible problem would be a composite structure wing laid up in a mold with the possibility of the mold contour changing significantly with age. This has been known to occur in the production of composite structure high performance gliders.

FAR section 23.605 requires an approved process specification for fabrication processes requiring close control to produce consistently sound structures. Traditionally, this requirement has been related to structural strength, but in the case of NLF technology it would also relate to achieving the required surface contour, smoothness, and waviness. The production method of painting an airplane is an example of a process that might also be critical to achieving NLF.

MAINTENANCE OF AERODYNAMIC SURFACES

FAR section 21.50 requires that instructions for continued airworthiness be provided, and for small airplanes, FAR section 23.1529 requires that they be prepared in accordance with Appendix G of FAR 23. This applies to both Type Certificates and Supplemental Type Certificates for which application was made after January 28, 1981. Appendix G of FAR Part 23 contains requirements for a maintenance manual. It would be necessary, for an airplane designed for operation with extensive NLF, to have information in the maintenance manual concerning routine care, repair, repainting, etc., of the aerodynamic surfaces and maintenance information relative to any laminar flow instrumentation that might be installed.

CONCLUDING REMARKS

In previous paragraphs, we have discussed the possible effects that the boundary layer state, laminar or turbulent, and loss of NLF may have on airplane performance, flying qualities, and flight loads. These effects would be more likely, or more pronounced, for airplanes with airfoils and surface quality designed for extensive NLF and for canard and tandem wing configurations with such airfoils and surface quality. The main effects of NLF evident to the pilot will be on performance and to some extent on flying qualities. Significant adverse effects on flying qualities and on flight loads must be avoided or corrected during the design and certification process.

If significant NLF is expected to be attainable, the applicant should present information early in the certification process on the possible extent of NLF, how maintenance of NLF will be assured, and the consequences of loss of a significant portion of NLF. Verification by test will likely be necessary. Flight testing techniques, such as the use of sublimating chemicals to determine the extent of NLF, and artificial means to force boundary layer transition may be required.

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