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CONSTRUCTING "GLOVED" WINGS FOR AERODYNAMIC STUDIES

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Abstract

Recently, two aircraft from the Dryden Flight Research Facility of NASA's Ames Research Center were used in the general study of natural laminar flow (NLF). The first, an F-14A aircraft on short-term loan to NASA from the U.S. Navy, was used to investigate transonic natural laminar flow. The second, an F-15A aircraft on long-term loan from the U.S. Air Force, was used to examine supersonic NLF. These tests were follow-on experiments to the NASA F-111 natural laminar flow experiment conducted in 1979. Both wings of the F-14A airplane were "gloved," in a two-phased experiment, with full-span (upper surface only) airfoil shapes constructed primarily of fiberglass, foam, and resin. A small section of the F-15A right wing was gloved in a similar manner.

Each glove incorporated provisions for instrumentation to measure surface pressure distributions. The F-14A gloves also had provisions for instrumentation to measure boundary layer profiles, acoustic environments, and surface pitot pressures.

Discussions of the techniques used to construct the gloves and to incorporate the required instrumentation are presented. Comparisons with the technique used to construct the F-111 NLF glove are made. Problem areas, with explanations and solutions when available, are addressed. Finally, an evaluation of the value and success of these techniques to modify airfoils is provided.

Introduction

Several flight experiments have been conducted using fighter-type aircraft as the parent aircraft for natural laminar flow (NLF) studies. In 1978-79, a major natural laminar flow study was conducted by the Dryden Flight Research Facility of NASA's Ames Research Center (Ames-Dryden) on an F-111 aircraft.[1] The methods used to install the airfoil used in that study[2] were successful in helping researchers to demonstrate that NLF was obtainable. This success lead to two follow-on experiments at Ames-Dryden in 1984-87, which used F-14A and F-15A aircraft.

The F-14A experiment, called the variable sweep transition flight experiment (VSTFE), was a major transonic NLF experiment involving a two-phase project plan. Prior to installation of either glove on the F-14A aircraft, however, a preliminary experiment was conducted to determine overall experiment feasibility. Small sections of the F-14A wing were gloved with fiberglass. During flight tests, researchers discovered that a wave developed in the glove along the wing and slat joint. Follow-up ground tests determined, however, that by constructing a glove with a foam core, the wave could be eliminated.

Glove I, a constant thickness, full-span upper surface glove, was installed on the F-14A left wing to clean up the basic F-14A airfoil and allow researchers to determine its aerodynamics. With the information gained from the cleanup glove, researchers designed a second airfoil shape for a specific flight condition that would subsequently be installed on the F-14A right wing.

The first glove experienced significant problems with surface finish cracking, which caused concern about the ability to obtain laminar flow. Attempts made to repair the cracks were generally unsuccessful until the center portion of the glove was resurfaced with additional layers of fiberglass. The repaired section was painted black to simultaneously permit the evaluation of an experimental flow visualization technique.

Glove II was installed on the right wing. Unlike the left wing glove, this glove significantly changed the airfoil and was designed to specific aerodynamic performance requirements. Moreover, unlike the left wing glove that was painted white to minimize the solar radiation effects on the fiberglass-resin integrity, the right wing glove was painted black, permitting use of pressure sensitive liquid crystals for flow visualization. Constructed slightly different, but operated within the same flight envelope, this glove did not show any signs of surface cracking during the entire 35-flight test phase. Figure 1 shows the F-14A aircraft with both gloves I and II installed.

A limited level of effort experiment was conducted on the F-15A airplane coincidental with other research. Researchers planned the experiment to study the ability to obtain natural laminar flow during supersonic flight conditions.[3] A minimum constant thickness glove with a surface finish conducive for natural laminar flow (Fig. 2) was installed on a small portion of one wing of the F-15A airplane. The objectives of this test required a flight envelope to a Mach number of 1.8 and an altitude over 50,000 ft. Except for a small amount of surface blistering, noted on one flight to Mach 1.8, neither construction nor operational anomalies were noted during the flight test program.

In both the VSTFE and the supersonic NLF experiments, instrumentation incorporation was integral to the glove construction. In all of the gloves, provision was made to measure surface static pressures. Provisions were made to measure boundary layer profiles, surface pitot pressures, and acoustic environments in the VSTFE gloves.

All gloves were subject, in part or in entirety, to a passive flow visualization technique which uses a pressure sensitive liquid crystal medium to depict flow patterns.

Lessons learned and experience gained during these two experiments have been substantial. The techniques used for glove installation discussed by Bohn-Meyer and Jiran[2] were refined or modified, resulting in a high level of success for these two projects. Those techniques, and resulting problem areas with suggested solutions or explanations when available, are considered to be of great value to the flight test community because they can be applied to a range of aerodynamic studies.

F-14A Variable Sweep Transition Flight Experiment

General Description

The F-14A test aircraft was a basic model except for the instrumentation system and a few experiment-driven configuration modifications. While no attempt was made to maintain aircraft symmetry, it was determined from wind tunnel tests and analyses that the asymmetric installation of the gloves would induce slight changes in rolling moments. Flight experience confirmed this analysis. The increases were barely perceptible by the flight crew, however, and were easily trimmed.

To eliminate potential problems with the fuel system, the wing fuel tanks were emptied for the flight test phase.

There were few flight envelope restrictions on the aircraft, but they were strictly enforced: maximum Mach, 0.9; maximum normal acceleration, 3 g; and no full stick deflections or abrupt control inputs.

The full-span gloves enveloped the basic wing from approximately the wing root to the wing tip. The primary test section paralleled the wing chord lines which also paralleled the fuselage centerline. The glove chord was terminated just forward of the full-span spoilers. Full spoiler control was available. However, the glove did wrap around the leading edge of the wing. The leading edge flaps, therefore, were locked in the full-up position. The lockup was mechanized by removing the flexible flap drive cable and pinning the gear box shared by the leading and trailing edge flaps. This design also deactivated the trailing edge flaps, resulting in increased landing speeds, but no other significant flight-operating limitations were planned.

The wing sweep was limited to between 20° and 35° during the flight test program. The inboard edges of the glove were shaped and chamfered during construction to permit the aircraft overwing fairing to slide over the glove's upper surface, if necessary, to obtain sweep angles > 35°. Thus, the presence of the glove did not restrict full wing sweep < 68° of the basic aircraft; however, sweeping > 35° would have subjected the glove to damage from the overwing fairing hard points which would slide on top of the inboard portion of the glove.

Throughout the primary test section, as for most aerodynamic studies of this nature, the airfoil coordinate locations, surface finish, and surface waviness limits were stringent: ± 0.010 in., 250 μm, and 0.002/2 in./in., respectively. The most inboard and outboard 20 in. of the glove was considered "area fill" regions. These regions, extending beyond the primary test section, were not constrained to the same stringent surface finish criteria of the primary test section. Owing to the inability to exactly define the basic wing airfoil, however, the airfoil coordinate location limits were lifted to ± 1/32 in. during glove construction. After the glove construction was complete, however, an exact definition of the coordinates, at specific wing stations, was determined by means of a splash (Fig. 3) or mold of the glove, at the specified stations.

Each glove was instrumented with chordwise rows of flush surface static pressure orifices and boundary layer rakes (Fig. 4). The left wing glove also incorporated three acoustic microphones and provision for use of an experimental surface pitot pressure measurement technique. Except for the microphones, which were in the glove, the instrumentation sensors and transducers were in various wing bays. Wiring from these bays was routed through the wing root pivot area and into the main instrumentation package in a fuselage compartment. Airspeed, altitude, angle of attack, and sideslip were obtained from a flight test boom installed in the radome. During flight, data were transmitted to a ground station and recorded onboard.

Preconstruction Tests

Prior to installing either glove, a preliminary flight experiment was conducted to determine overall experiment feasibility. Fiberglass-only gloves were installed on small sections of the F-14A wing. During flight tests on these gloves, researchers discovered that a wave or bump developed in the glove along the wing–slat joint, most notably in the center of the wing–slat joint where the slat itself is split. The existence of such a wave seriously jeopardized the overall experiment success. Figure 5 shows a postflight view of the glove.

In the ground test that followed, various glove construction methods were evaluated for the ability of the materials to absorb the differential deflections of the wing and slat. In these tests, four small sections of the F-14A wing, along the wing and slat joint (Fig. 6), were gloved using various construction techniques. Next, using hydraulic jacks under the wing, the wing was deflected to simulate 1-g flight conditions. Changes in curvature were measured along the joint. The existence of a wave or bump disqualified the technique for use during total glove construction. It was found that a glove with a foam core of no less than 1/2 in. could absorb the differential deflections. The tests also demonstrated that not attaching (bonding) the glove to the wing or slat within 2 in. of the joint minimized the magnitude of the wave generated by the differential deflections. A more detailed explanation of the 1-g load test is provided later in this text.

Lessons learned during previous glove installations on NASA's F-111 aircraft[2] were reviewed to determine the best installation techniques for the left wing (glove I) VSTFE glove on the F-14 airplane. Because of problems encountered during the glove I flight test phase, however, a significant level of effort was expended to develop the techniques necessary to construct a flaw-free second glove. Lessons learned during the construction and flight test on the first VSTFE wing glove, therefore, were used to design, fabricate, and operate the right wing glove. This approach resulted in the mistakes being limited to the left wing glove and an extremely successful flight test program on the right wing glove.

The steps used to install the left wing glove are described in detail. In areas where installation differences exist between the left and right wing gloves, a discussion of how and why the changes were made is provided.

Left Wing, Glove I

To determine the baseline airfoil characteristics of the F-14A wing, a full-span cleanup glove (Fig. 7), with a surface finish conducive to natural laminar flow, was installed on the aircraft left wing. Thirty-five flights were conducted throughout a Mach number range $\leq$ 0.9 and at an altitude $\leq$ 45,000 ft, providing the data base for developing the right wing glove contour and construction methods.

The thickness of the cleanup glove was a constant 5/8 in. and enveloped the wing from butt line 130 to 355 and from 15 percent chord (lower surface) to 60 percent chord (upper surface). The thickness was based on the preconstruction tests which determined the effect that the wing-to-slat joint movement had on the surface waviness and on an opinion that a thinner glove would not permit incorporation of the required instrumentation. The glove incorporated three rows of surface static orifices, two boundary layer rakes, three microphones, and provided for 40 surface pitot measurements. All instrumentation–plumbing and mounts were built in during glove construction, resulting in a continuous laminar flow airfoil throughout the glove span.

To minimize the effects of solar heating and ultraviolet radiation on the fiberglass-to-resin bond integrity, the glove was painted white—the color known to result in the smallest temperature rise for a given exposure.[4] The center test section later was painted black to permit experimentation with a pressure sensitive liquid crystal medium that provided flow pattern imaging.

Installation Techniques

Step One: Preparation of the Wing. The wings of the F-14A carrier aircraft were lightweight (approximately 2000 lb) and relatively easy to remove and transport, one of the luxuries afforded by using this airplane for the VSTFE project.

Once the wing was removed from the aircraft, it was installed in a factory-made transportation dolly. A wing installed in the dolly could be rotated to expose the lower surface almost as readily as the upper surface, thus minimizing the difficulty of finishing the lower surface of the gloved wing.

Since the majority of the wing skin is titanium, preparation for glove installation was a critical step. Available research showed that special preparation and installation techniques would be required to obtain a permanent bond between the titanium skin and the glove. However, since a permanent bond was not desired (a bond that could withstand the primarily shear loads of a flight environment was required), a short ground-test program was conducted to evaluate preparation techniques. Coupons were bonded to the wing using various preparation techniques. After the bond cured, the coupons were pulled off while noting and measuring the bending and tensile forces required to do so (Figs. 8a and 8b). In general, these tests resulted in the following procedure: (1) all paint was stripped from the wing surface using a standard industrial paint stripper; (2) the surface was sanded with 80-grit sandpaper to remove loose particles; and (3) the surface was thoroughly wiped with MEK to remove residual contaminates or dust particles.

Step Two: Initial Bonding. After the wing surface was cleaned properly, an initial layer of unidirectional fiberglass cloth was bonded to the skin. This layer of glass would provide two important features for the glove installation: (1) a buffer layer that could be peeled off of the wing skin after flight tests, and (2) a sealed surface to bond the foam core.

The fiberglass buffer layer was bonded to the titanium with the fiber orientated parallel to the chordline of the wing. To minimize excess resin and ensure maximum bonding area, the glass layers were vacuum-bagged[2] during the cure process.

Special attention was given to the wing and slat joint areas. As stated previously, flight and ground tests also demonstrated that the effect of the differential movement of the wing and slat could be eliminated by the following: (1) not permitting the initial buffer layers of fiberglass to be bonded to the wing and slat within 2 in. of the joint, and (2) incorporating a foam core interface along the length of the joint. Thus, during the initial bonding phase, Teflon tape was applied along the joints to the skin of the wing and slat. The bonding of the initial buffer layers of glass bridged from wing to slat and slat to slat, but did not bond to the surface within 2 in. of the joint lines.

Step Three: Foam Core Installation and Fiberglass Closeout. Unlike the two-part spray-on foam used for the F-111 natural laminar flow glove, the foam used for the F-14A and F-15A gloves was precut closed cell low-density polyurethane foam. This foam type was selected for ease of handling and for the more uniform density distribution compared to the spray-on expanding foam. Like the spray-on material, the foam was easily shaped after installation.

Since the original intent of the left wing glove on the F-14A aircraft was to clean up the wing to provide researchers with some basic airfoil data, a constant thickness foam core was selected. The 1/2-in. thickness was selected based on the previously mentioned ground tests. The total (finished) thickness of the glove, therefore, would be 5/8 in., the anticipated minimum thickness for building in integral instrumentation. (This estimate was later shown to be too pessimistic; the finished F-15A glove thickness was only 1/4 in.)

The technique to install the foam core was straightforward. Precut foam was installed using standard vacuum bagging techniques.[2] This minimized excess resin, while maximizing the quality of bond to the wing. After the foam core was successfully bonded in place, it was sealed by wiping the exposed foam with a microballon-resin slurry. Four layers of bidirectional fiberglass cloth were applied over the entire surface. As in the previous bonding steps, this layer of glass was vacuum bagged during application. Except along the upper surface trailing edge where the closeout was an abrupt square corner, the foam was chamfered along the edges, and the fiberglass cloth was extended beyond the foam onto the initial layer of glass. This effectively closed the fiberglass-foam-fiberglass sandwich.

Step Four: Template Setup. Next, the templates, which were fabricated using a numerically controlled milling machine to specific airfoil coordinates, were fit-checked on the wing. The templates, when properly located on the wing (Fig. 9), would provide a gage for the final outer moldline contour of the glove. This gage was an exact representation of the desired glove outer moldline contour. The templates, however, were cut assuming a basic airfoil shape and then adding a 5/8-in. thickness to that shape along the span and chord of the wing. The basic F-14A wing, however, did not prove to be an exact replica of the designed airfoil. Thus, the fit of the templates was not good; each had to be located where it fit best, with concentrated effort on the templates for the static pressure orifice rows. In some cases, this best fit resulted in rotating upwards, as much as 1/4 in., the trailing edge of the template. This caused researchers some concern about the effect this trailing edge thickness change would have on the aerodynamics of the airfoil; however, the fears of adversely affected separation were not realized in flight.

After the templates were located, two removable template-locating mounts were bonded to the wing surface. This permitted relocation of the templates during finishing steps.

Step Five: Instrumentation Plumbing Incorporation. The left wing glove incorporated provisions for two boundary layer rakes, three 20-orifice surface static pressure rows, and 40 surface pitot pressure orifices. In addition, three microphones for acoustic environment measurements were incorporated. Researchers required that all tubing and mounting structures for collecting these measurements be located inside the glove and routed to the transducers or other instrumentation hardware in compartments along the glove trailing edge upper and lower surfaces. Access to the lower surface transducers was limited since the glove extended beyond the compartments holding the transducers.

To facilitate pressure plumbing patching changes, doors were built into the glove's lower surface. This permitted access to a patching manifold, external to the compartment that housed the transducers. All pressure plumbing was routed to these manifolds (Fig. 10).

Surface statics and surface pitots: Previous successful experience with surface static installations was the cornerstone for the work on this glove. Because the requirements for the surface pitots were the same as those for the statics, the installation technique was the same. Target cups approximately 1 in. in diameter and 1/4 in. high were made from aluminum barstock. The foam and outer glass were removed from the wing in areas where the target cups and tubing were to be installed. Stainless steel, small diameter, thin-walled tubing was used to connect the target cups to the pressure transducers in the lower wing compartments. The tubing was routed as required (Fig. 11), resulting in a 170-tube maze that ultimately terminated in patch panels. All tubing lengths were continuous, resulting in some lengths > 16 ft.

To ensure a system with no leaks, the tubing was attached to the cup (epoxied to the cup through a hole in the cup sidewall) before the tubing–cup assembly was installed. The assembly was placed in the troughs, the tubing occasionally tacked in place, and the target cup epoxied onto the initial layer of fiberglass. Once again, to ensure a system with no leaks, a fillet of thickened resin was wiped around the target cup bonded edge. Finally, a leak check was performed before the tubing assembly was covered.

To meet the requirement to space the orifice target cups every 2 1/2 percent around the relatively thin leading edge (instead of the 5 to 10 percent chord spacing along the upper surface), the 1-in. diameter target cups were replaced by 3/8-in.-wide target troughs (Fig. 12). This permitted tight spacing of the targets; therefore, more frequent static orifices could be incorporated.

After the cups and tubing were in place, the corresponding template was installed above the static orifice rows. A line was scribed in the template, depicting a perpendicular to the upper surface of the cup at each orifice location. The orifices would be drilled later using the scribed template as the reference. Having the angle on the template was especially important on the leading edge where the cups were so close together, and the angular change from perpendicular to perpendicular was great. To be able to locate the surface pitot cups, a paper template was made showing the exact cup locations.

Boundary layer rakes: A hard mount for the boundary layer rake, which permitted two orientations for the boundary layer rake, was required. In addition, researchers required flexibility to remove the rake, or replumb the rake for a specific test. This resulted in the incorporation of a rake tubing patch box adjacent to the rake hard mount. Tubing was routed from the lower surface patching manifold to the boundary layer rake patch box. Within the patch box, the rake and glove tubing could be connected, as required, using rubber tubing as the bridge conduit.

Provision for the boundary layer rake installation was made much the same way as that for the static pressure orifices. The outer layer of fiberglass and core foam were removed, and the aluminum hard mount and patch box were epoxied in place. There was no need to seal around the tubing in the patch box as each tube was continuous to the patching manifold. A paper tracing, depicting the exact orientation of the mount and the patch box, was made for future use when installing the rake.

Microphone housing and conduit: Three microphones were installed in the left glove. To do this, a housing was constructed in much the same manner as the boundary layer rake mount and patch box, except that the housing was fabricated from prefabricated fiberglass lay-up. This was done to minimize thermal discontinuity which might affect microphone performance. Flush covers were blended into the glove surface after the microphones were installed.

The path for the signal wiring was a 1/4-in. tubing conduit routed directly aft of the housing to the instrumentation bay aft of the glove.

After all the integral instrumentation was incorporated, the tubing troughs and the foam cutout areas were refilled with foam blocks. Subsequently, these areas were finished with a fiberglass layer consistent with the techniques described in step three.

Step Six: Contouring the Glove. Shaping the glove to final contour was the most tedious and time-consuming effort throughout the entire glove construction process. This effort was consistent with Bohn-Meyer and Jiran[2] with minor modifications to accommodate differences in construction techniques.

The templates were installed using the template mounts (step four). Prior to this installation, however, a release agent was applied to the template edge representing the final glove outer-mold line. Simultaneously, a thick layer of automotive body putty was applied to the glove at each template station. As the template was installed, an impression of the desired outer-mold line (OML) was made in the putty. Excess putty was removed before it was completely cured. An accurate

OML representation resulted when the template was removed after the putty was finally cured. Referencing the templates, chord percentage lines were marked on the OML representation.

As stated earlier, the templates were rotated as required to account for differences between the wing and the template. This resulted in a gap as much as 1/8 in. between the fiberglass unfinished glove and the template. The putty OML representation gave an accurate account of the chordwise gap variance. To quickly build up the surface, automotive body putty (filler) was used. Initally, the putty was simply spread between the OML rails, in layers, until there was only a 1/16 to 1/32 in. height difference between the area and the rail. Then a screed bar, which spanned across at least two rails, was used to spread the mixture and wipe away any excess. The process was repeated several times until a span and chordwise contour that matched the OML rails resulted. Figure 13 shows the glove after contouring with autobody putty.

Since the templates represented the final glove contour, without allowance for paint thickness, the entire glove was sanded with 6 to 8 ft spline boards (Fig. 14). Approximately 0.005 to 0.010 in. of putty was removed to account for the paint primer and final paint layers. After several applications of a polyester primer, which was applied and sanded, a finish coat of white polyester paint was applied. The glove was sanded with 220-, 320-, 400-, and 600-grit paper, resulting in a surface finish meeting the construction criteria.

Step Seven: Postcure and Finishing. Anticipating some postcuring shrinkage, the entire wing glove was subject to a postcuring heating. A crude oven was built around the gloved wing in the transportation dolly. Hot air was used to elevate the air temperature and maintain an oven temperature of approximately 135°F for 6 hr.

The postcure process completed, the final paint layers were rechecked for compliance to coordinate and waviness criteria. Any deviations were corrected either with additional spline sanding or an additional paint layer application and subsequent spline sanding.

Step Eight: Instrumentation Final Location. To locate the static pressure transducer target cups now buried within the glove and not visible from the finished surface, the templates were once again placed on the wing. Recall that lines had been scribed into the templates depicting a perpendicular to the target cup itself. Using a pin vise in a homemade adjustable angle holding fixture, 0.030-in. holes were drilled through the glove surface and into the target cup at each scribeline. The angle of the drill matched that of the scribe line—ensuring that the hole did penetrate the cup. To minimize contamination of the cup volume with glove and cup material chips and to confirm a good hit, a constant but very low pressure air source was applied to the tube corresponding to the target cup. When the cup was broken through, the pressure would drop, signifying the orifice was correctly located and drilled. (Low pressure air was necessary—use of higher pressure air may have resulted in popping the bond between the cup and glass, thereby destroying the target cup potential.) Around the leading edge, it was necessary to use a drill stop to prevent the drill from piercing through the thin target walls and entering an adjacent target wall, thereby destroying both cups.

Static pressure and pitot pressure orifice holes were drilled in the same way.

Step Nine: Final Checks and Spot Finishing. After all orifices were drilled, covers fabricated and fitted, the wing was reinstalled on the aircraft. During construction of the glove, the wing tip section was not built up because the wing-holding fixture was in the way. In addition, access holes to wing hardpoints used to install the wing had to be cut in the glove prior to wing installation. Therefore, a limited amount of finish work had to be done while the wing was on the aircraft. The tip area was built up in the same way the glove was built up except that no vacuum bagging or postcuring was done. The access holes were refilled with the plug that was removed. Autobody filler and paint buildup were used to feather–fair the plugs into the original contour.

The templates were installed once more for the final check of the contour. This time any differences between the template and the contour were documented by making a mold of the contour on the template. These templates were then accurately measured in an X-Y chordwise plotter, providing a permanent record of the airfoil contours.

Step Ten: 1-G Load Tests. To document the contour (curvature) changes due to a 1-g wing deflection (the condition expected during most of the test flights), a load test was performed.

Wing glove waviness was measured at three wing stations for two different load conditions. The first condition, wing unloaded, provided a baseline measurement of the glove surface waviness. The second condition resulted in a wing deflection similar to that obtained during 1-g flight.

The load was simulated by jacking the wing, from the lower surface, at four span stations per wing. Each hydraulic jack was adjusted individually to obtain the wing deflection specified for the associated wing station. Since the jack pad supplied a point load only, a system to spread the load chordwise was devised. Lengths of I-channel were placed on the jack pads, arranged chordwise, between the leading and trailing edge spars. Next, high-density polyurethane foam blocks, cut smooth on one side and cut to match the contour of the lower wing surface on the other side, were placed on top of the iron I-channel. Finally, high-density foam rubber was placed on top of the foam block. As the jack was extended, the load was spread chordwise, ensuring a reasonable representation of 1-g deflection. At no time did the foam crush under load. Figure 15 shows the general arrangement of the load test with the jacks adjusted to approximately 50 percent of 1-g load.

Measurements were obtained while the wing was loaded, using a waviness gage. The waviness gage is a mechanical deflection dial gage with support feet 2 in. apart. It was also configured with a wheel to measure distance from a starting point (Fig. 16). Electrical signals from the dial gage and the distance wheel were automatically plotted when the gage assembly was manually moved chordwise over the glove.

In general, this test showed that while the deflected wing was not as smooth as the unloaded wing (Fig. 17), the wave amplitude of the deflected wing was still less than the 0.002 in./in. specified for glove construction.[5]

Problem Areas

A quick comparison of the techniques used to construct the F-14A left wing glove and the F-111 NLF glove[1] shows that the differences in methods were insignificant except for one major item: the F-14A VSTFE glove was constructed on the wing with 100 percent contact area, whereas the F-111 glove was constructed on a plug, then bonded to the wing with perhaps 60-70 percent contact area. In addition, the F-111 wing is a rigid 4000 lb (empty weight) wing; the F-14A wing is a fairly flexible 2000 lb wing. The rigidity difference may be a significant factor when considering how to construct a glove for aerodynamic studies.

Despite the fact that the two aircraft were operated in much the same manner, the F-14A glove suffered from an interesting and severe case of surface cracking—which may never be fully understood.

After the first flight, a postflight inspection determined that the glove was flaw-free with no cracks, delaminations, or other notable defects. A second flight postflight inspection noted a glove disbonding on the outboard trailing edge, but no surface flaws were detected. This disbond was repaired by injecting resin between the glove and wing. After both flights, the aircraft was stored in an enclosed hangar.

The morning after the second flight day, however, during a preflight inspection, there was a different story to tell: the glove surface now had numerous random direction, random location surface cracks–with no apparent relationship to each other or to submerged instrumentation. Some of the cracks measured steps of less than 0.001 in. while others measured more than 0.003 in.–too much for a laminar flow research experiment.

Suspecting only surface defects, one crack was selected for inspection. The finish layers of filler and paint were removed to expose the glass. Close visual inspection of the glass revealed no apparent defects.

The surface was spline sanded using a lacquer putty to fill the cracks, then returned to flight status. The cracking of the surface continued with new random cracks appearing after the flight, despite limiting flight control inputs to half stick and deactivating the outboard set of spoilers to minimize the flexing of the wing. Tap testing for defects, disbonds, and delaminations continued with no changes noted. The spline sanding approach continued until researchers determined that the quality of the data was being jeopardized: the glove surface had to be repaired.

Repairing the glove surface was an extensive effort. Instrumentation was removed and all orifice holes were plugged with autobody filler. Next, all layers of paint and body fillers were sanded. The exposed glass layers were inspected, and a few cracks in the glass layers were located. The area around one of the cracks was removed and the foam inspected. No obvious flaws were found in the foam. The glove was resurfaced using the same techniques described in step six except that prior to contouring with autobody putty, two additional layers of fiberglass were applied over the original glass layers. Autobody putty and paint fillers were used again to bring the glove to final contour. In addition, two strain gages were installed on the glove surface. Subsequent flights resulted in a similar surface cracking problem. Although no significant strain levels were recorded, preflight inspection prior to the second flight revealed the cracks were back. No cracks were noted on the postflight.

Meanwhile, tests were performed in a laboratory on the stress-strain relationship and levels required to fail representative fiberglass laminates in tension. The measured values, compared with the flight environment values, did not provide conclusive evidence to support any theory on the cause of the problem. The project continued flight operations despite the cracks, returning to the postflight spline sanding schedule.

A last effort was undertaken with a twofold purpose: (1) eliminate the cracks in one test section, and (2) evaluate the use of a black-painted surface for pressure sensitive liquid crystal flow visualization. The surface paint and fillers were removed from the center test section. An additional layer of glass was applied and the surface refinished—this time with a black polyester paint and a minimum of fillers.

Ultimately this change had the most positive effect on the minimization of glove surface cracking:

fewer than normal cracks appeared on the black surface and many more flights were flown before they began to appear.

Throughout this entire period, no cracks chipped, disbonded or delaminated. Flights on this glove continued until the end of the entire project—with the cracking surface never appearing to worsen.

As a secondary effect of the crack propagation, pressure orifices began to leak. The cracks were often created in an air path, between two orifices, resulting in erroneous representations of local pressure measurements. When these orifices were identified, one of the orifices was filled, and a new, offset hole was drilled into the target cup. This proved to be effective in stopping the orifice-to-orifice leak problem.

As might be expected, disbonds at the outboard trailing edge of the glove were a constant problem. Each occurrence was treated by injecting resin between the wing and the glove to effect a localized reattachment. The disbond area never grew beyond its original isolated section.

Orderly cracking did occur around the metal hardpoints embedded in the glove. This cracking, it was assumed, was due to differences in the thermal expansion rates of the fiberglass glove and aluminum mount. It is noteworthy to point out, however, that at no time did these cracks develop into a critical structural concern.

Right Wing, Glove II

A full-span variable thickness natural laminar flow glove, designed for optimum performance at a Mach number of 0.8, was installed on the right wing (Fig. 18). (The glove thickness varied from 1/2 in. at the trailing edge to approximately 4 in. overhanging the basic wing leading edge.) The right wing glove enveloped the wing in the same manner as the cleanup glove.

Instrumentation plumbing, installed during glove construction, was increased to four rows of surface static pressure orifices while the surface pitot measurement plumbing was deleted. Mounts for two boundary layer rakes were incorporated. There were no acoustic environment measurements made on the right wing glove.

Unlike the left wing glove, this glove was painted flat black. The color was selected to facilitate the use of a pressure sensitive liquid crystal medium that provided a means for real-time visualization of the flow patterns. Since black colors have been shown to absorb solar radiation which degrades resin bonds, special operating restrictions were imposed to minimize exposure time.

The changes in fabrication techniques used to construct the right wing glove are described later in the text.

Installation Techniques

During the left wing glove flight test phase, several problems, which affected the project direction and data quality, were encountered. Because of the magnitude of these problems, several changes were made in the methods used for the construction of the right wing glove.

In general, however, the techniques used to construct the right wing glove were the same as those used to fabricate the left wing glove. While some of the changes were incorporated in an attempt to correct the problems encountered with the left wing glove, others were made because the glove II shape was significantly different than the basic wing.

The differences between the left and right glove construction are described in this section. In addition, other glove specific changes are provided.

1. No aluminum hardpoints were used.

Cracks appeared in high concentrations in areas where the metal mounts were located on the left wing glove. Though never verified, these cracks were most likely due to thermal expansion differences between the glove material and the metal mounts. In lieu of metal, prefabricated lay-ups of resin and fiberglass were used with metal fastener receptacles bonded into the lay-ups as required for the instrumentation component mounting.

The use of stainless steel tubing as the conduit for all pressure measurement plumbing remained unchanged.

2. Very limited autobody putty or fillers were used.

The surface cracking, which is discussed in the left wing glove Problem Areas section, was most likely directly linked to the flexibility of the basic wing and the quantity (thickness) of autobody putty and paint fillers used during glove finishing. Again, although never verified, the majority of the cracks most likely were caused by the inability of the autobody putty and paint fillers to accept and absorb the energy of deflection without deformation (cracking). The highly flexible F-14A wing was subjecting the glove surface to constantly changing g-levels and directions.

For the right wing glove, the contour was obtained by first installing foam blocks, precut to slightly oversize of the final contour. The blocks were shaped to just undersize of the final contour, permitting installation of the final glass layers. The fiberglass was actually sanded to contour prior to application of a minimum of fillers and the final paint.

This change required working with an exposed foam surface. For this reason, the density of the foam was also changed to a slightly higher density that would accept more punishment during the early construction phases.

3. High-temperature resins were used.

One of the objectives of the second phase of the VSTFE project was to obtain flow visualization data using a fairly new technique which employs a pressure sensitive liquid crystal medium to depict the location of transition or other aerodynamic flow phenomena. To effectively use this medium, however, we required a black surface. To minimize the adverse effect that solar radiation would have on bonding within a black resin construction, a high-temperature resin was a requirement. Therefore, a resin that accepted a postcure to 180°F, the maximum temperature expected during the flight test phase, was selected. Postcuring at this temperature, prior to paint application, ensured a stable bonded glove that would be affected minimally by solar radiation. After postcuring, the final surface paint was applied to the glove.

Problem Areas

The design–construction technique changes used for the right wing glove, combined with some operating changes, resulted in a right wing glove that was essentially flaw-free throughout the entire flight test program.

There were two small areas where cloth was transferred. The weave of the fiberglass layers beneath the paint began to show externally through the paint. These areas were not postcured. They were finished after the wing was installed on the aircraft.

Two operating rules were significantly changed for the aircraft while the right wing glove was installed. First, no stick deflections beyond half stick were permitted (unless necessary for emergency measures). This minimized the magnitude of the wing deflections in flight. Second, since it was possible that the tips drooping after flight caused strains in the cold-soaked glove, which may have resulted in glove surface imperfections, postflight storage of the aircraft included propping up the wing tips. The propped configuration more closely resembled the construction and inflight configuration. No surface cracking was noted throughout the flight program.

F-15A Supersonic Natural Laminar Flow (SSNLF)

A standard F-15A aircraft was used to piggyback a limited study to determine the feasibility to obtain natural laminar flow under supersonic flow conditions. An instrumentation system was carried in the aircraft fuselage.

The glove was flight tested to a Mach number of 1.8 and an altitude of 50,000 ft to determine the feasibility of obtaining significant amounts of laminar flow at supersonic speeds.

A partial span constant thickness natural laminar flow glove was installed on the right wing of the aircraft (Fig. 19). The 1/4-in. thickness of this glove was determined to be the minimum for successfully incorporating pressure orifices. The glove spanned from butt line 170 to 218 and wrapped around the wing leading edge to approximately 5 percent. Like the F-14A VSTFE gloves, integral surface static pressure measurement was provided for during glove construction. The glove was initially painted white. After documenting the pressure distributions, it was painted black to permit use of the pressure sensitive liquid crystal flow visualization technique. Just as for the F-14A gloves, surface finish and waviness requirements were stringent: 250 μm and 0.002/2 in./in., respectively, but like the cleanup glove, the airfoil coordinate accuracy was generous ($\pm$ 0.030 in.).

There were no special operating limitations imposed on the F-15A aircraft due to the installation of the glove, and all obtained data were telemetered to the NASA ground station.

Installation Techniques

Previous experiments, conducted by NASA on the F-15A aircraft, have shown the F-15A wing to have a pressure gradient which is desirable for obtaining laminar flow. The glove was installed, therefore, primarily to clean up the local wing aerodynamic environment. The glove thickness design criterion was specified as minimum thickness, yet the incorporation of two rows of flush surface static pressure orifices was a requirement. It was subsequently found that a foam core of 1/8 in. provided enough thickness to incorporate the orifice rows. The glove-finished thickness was 1/4 in.

Construction techniques were generally the same as those used to construct the F-14A VSTFE gloves. Like the F-14A VSTFE right wing glove, the use of autobody putty and paint fillers was kept to a minimum. There was no postcure process for this glove. The glove was initially painted white. After documenting the pressure distributions, the glove was repainted black to permit use of the pressure sensitive liquid crystals for flow pattern visualization.

Problem Areas

Subject to a high-altitude and high-speed flight environment, there were no structural problems with the F-15A supersonic glove. There was, however, a significant development of surface finish blistering, resulting in the end of the experiment.

After several flights to high altitude and Mach number (50,000 ft and 1.8, respectively), a number of small blisters appeared in the glove surface. Approximately 0.060 to 0.100 in. in diameter and 2 to 10 thousandths high, the blisters did not break the surface; however, they did create a serious defect in the glove which prevented researchers from measuring accurately the existence of natural laminar flow.

Interestingly, the glove had been subject to the same flight conditions on several other flights, with no surface defects noted. During the incidental flight, however, researchers noted that the atmospheric temperature, at altitude, was higher than normal. The higher atmospheric temperature resulted in a higher glove surface temperature. As the aircraft accelerated to 1.8 Mach, the higher glove temperature may have caused the formation of gas bubbles in the glove (from the outgassing of the resins, autobody fillers, and paints at the elevated temperature). At the higher altitude, the gas bubbles may have expanded, resulting in blistering of the glove surface.

As was stated in the installation section, the F-15A supersonic natural laminar flow glove was not postcured during construction. Postcuring stabilizes the construction. If the proper resins are used and the postcuring temperature is properly selected, the postcure process may result in less gas retention in the construction. Without the gas retention, the formation of gas bubbles, which may cause blistering, would be minimized even if the environmental factors are conducive to gas expansion.

Recommendations and Concluding Remarks

As concluded in Bohn-Meyer and Jiran,[2] the use of techniques similar to those discussed to modify an airfoil are still viable methods. A few additional considerations, however, must be addressed:

- General construction methods have not changed. A glove bonded directly to the parent aircraft is desirable. This ensures that contour real-time compensations for physical differences are made with less impact. The final contour more closely represents the desired contour since the physical differences are compensated for earlier in the construction process. The F-111 bond-after construction method, although effective, required extra contouring after installation, and did not achieve the same level as either the F-14A gloves or the F-15A glove.
- In all constructions, compensation for the carrier vehicle characteristics must be made. Rigid winged aircraft installations apparently are less susceptible to developing surface flaws than more flexible winged aircraft test beds.
- The techniques used to incorporate instrumentation into a glove have been shown three times to be effective in obtaining quality data. Few changes were made in the instrumentation installation between the F-111 and the F-14A and F-15A experiments. The changes that were made demonstrated
- that surface static pressure measurement instrumentation could be incorporated into a glove of no more than 1/4-in. thickness.
- The use of filler materials should be minimized. Even with flexible fillers, thick layers of filler material seem to be more susceptible to development of surface flaws than a surface fabricated with a minimum of the same materials. To use this approach, however, requires time-consuming sanding of the final fiberglass layers to contour, after carefully shaping the underlying foam.
- For applications where high altitude and high Mach numbers are anticipated, consider a postcure process before exposing the glove to high altitude and Mach number conditions. The postcure process may minimize gas retention, and, therefore, the likelihood that surface blistering will occur.
- For applications where high altitude and high Mach numbers are anticipated, materials selection is critical. The F-15A experiment results seem to indicate that the materials used for the F-15A glove were at the limit of their ability to withstand the temperature–pressure environment of supersonic flight. The materials used to construct the NASA F-15A supersonic natural laminar flow glove may not be suitable for the construction of gloves on aircraft operating in a flight environment > Mach 2.
- Maintenance, in general, can be troublefree. Surfaces were cleaned with an all-purpose cleaner after each flight. Critical areas were tap tested for evidence of a disbond from the aircraft. As a postflight requirement, the flexible wings of the F-14A aircraft were propped during the glove II flight test program, perhaps relieving the glove of internal stress while it warmed up.
- Construction tasks should always be handled by experienced workers. If aerodynamics is the reason for the experiment, the skill level of the employee may greatly affect quality.

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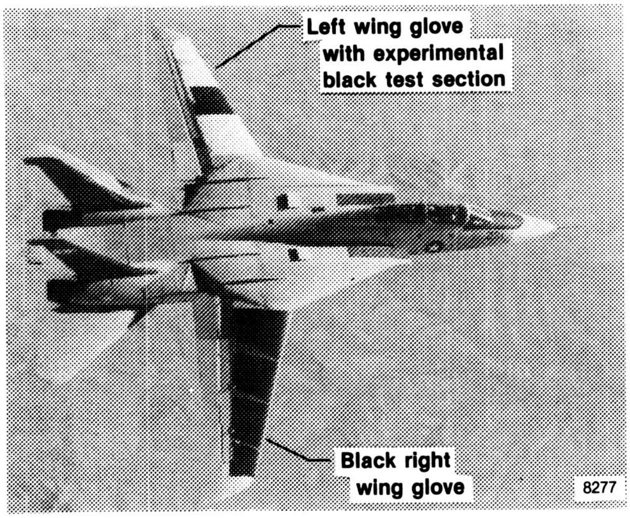


Fig. 1 The variable sweep transition flight experiment F-14A with both gloves installed.

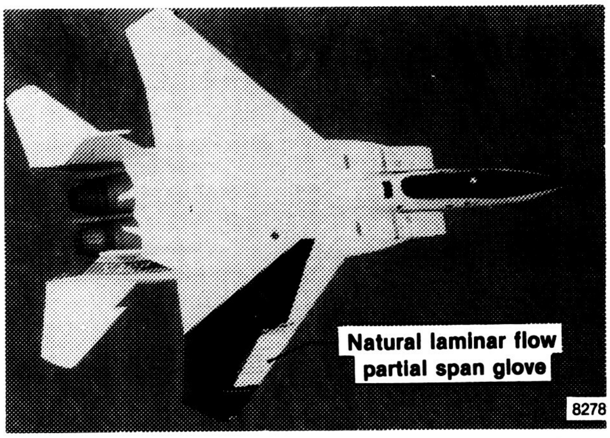


Fig. 2 The F-15A with the partial span glove installed.

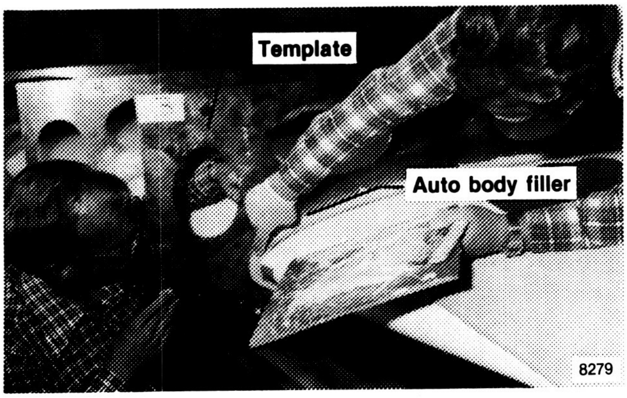


Fig. 3 Creating a splash to document the final contour of the glove.

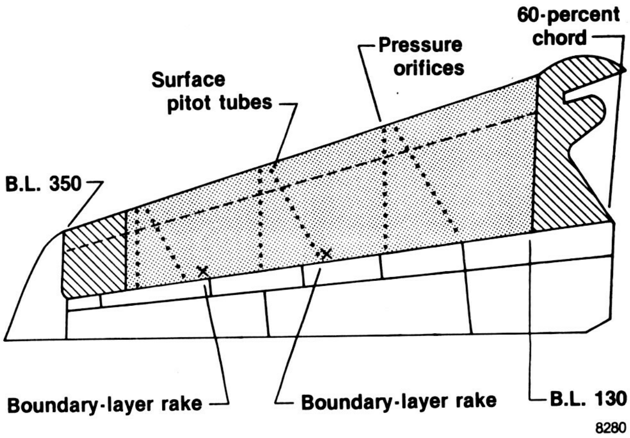


Fig. 4 Instrumentation layout and glove planform.

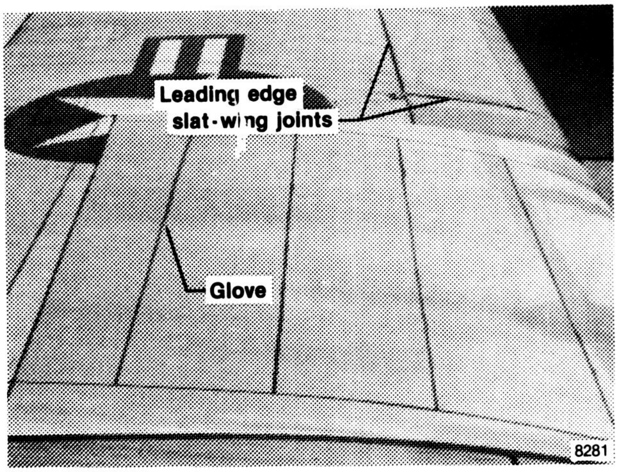


Fig. 5 Fiberglass only glove used to determine experiment feasibility.

Fig. 6 Test coupons installed for 1-g load test.

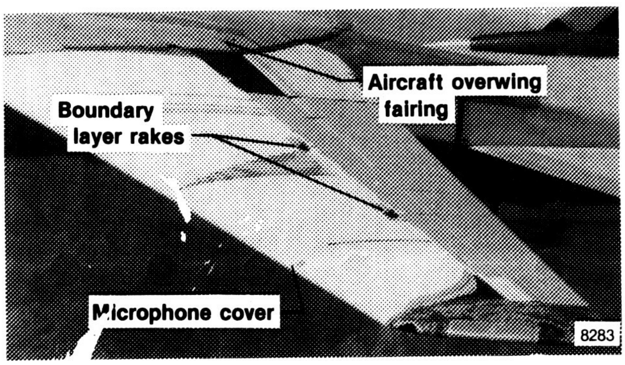
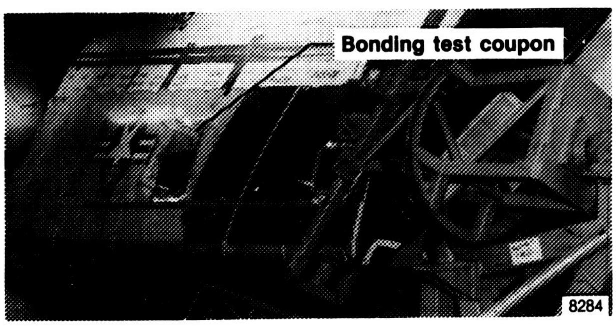
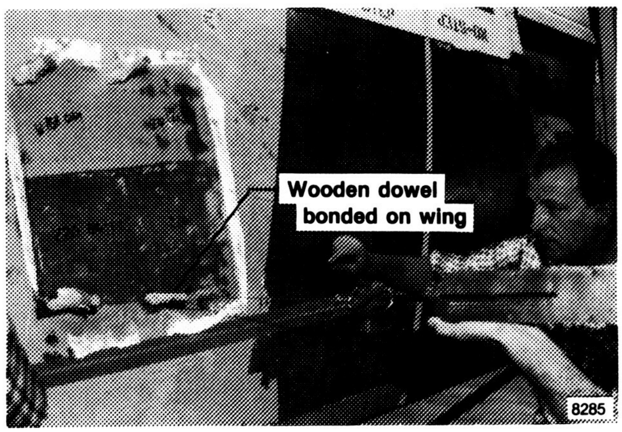


Fig. 7 Left wing cleanup glove.



(a) Bonding test coupons installed.



(b) Bonding test-tension measurement.

Fig. 8 Wing with bonding test coupons.

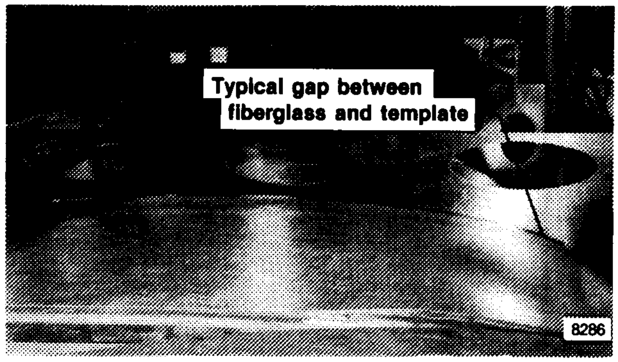
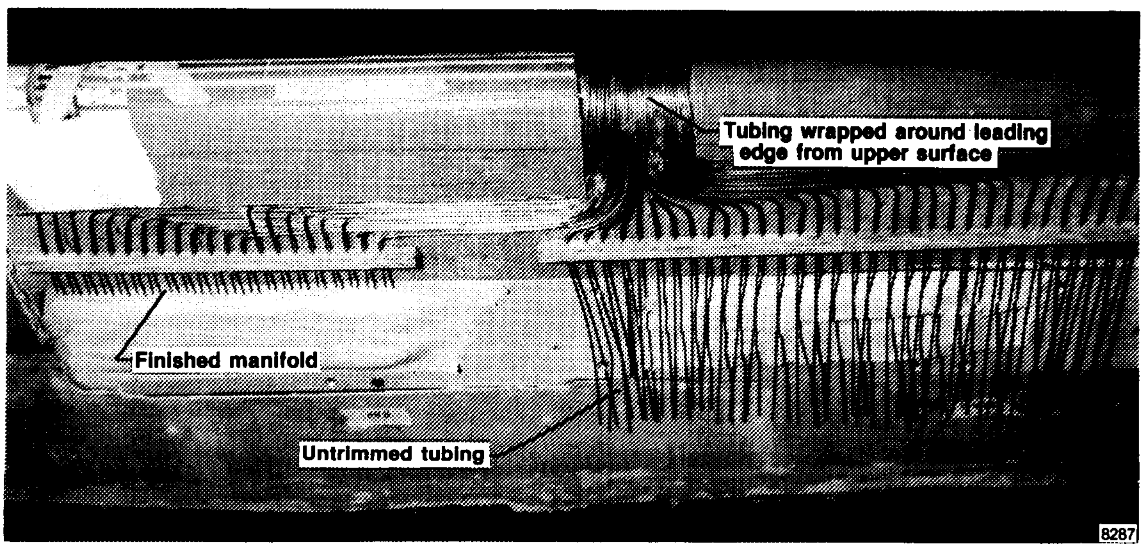


Fig. 9 Cleanup glove with outer fiberglass and templates installed.



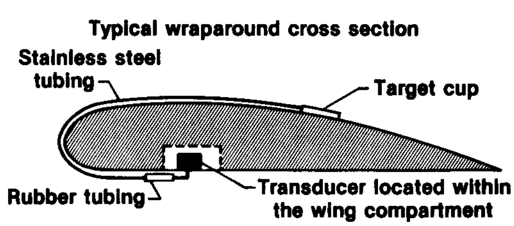


Fig. 10 Typical plumbing routing and lower wing patching manifold.

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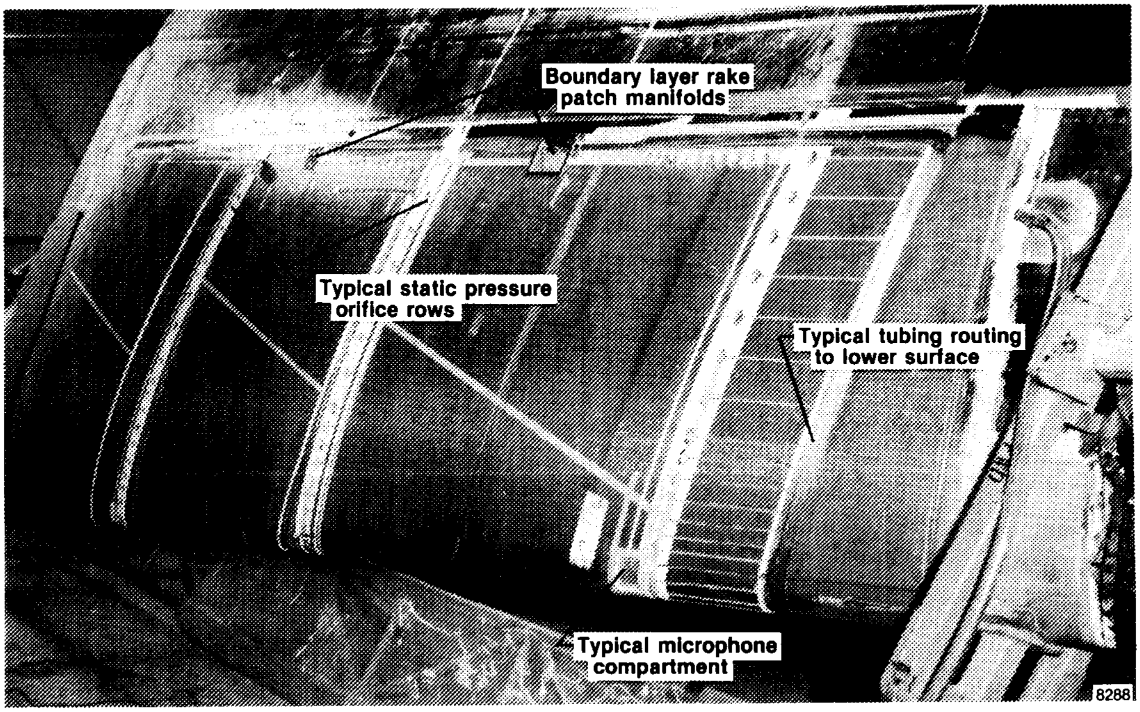

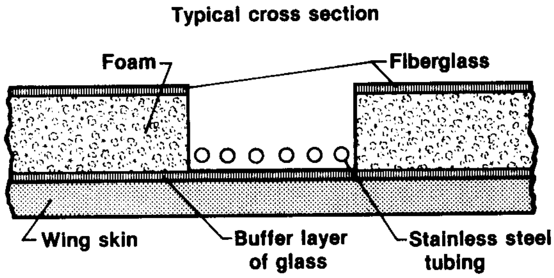

Fig. 11 Left wing glove instrumentation tubing layout.

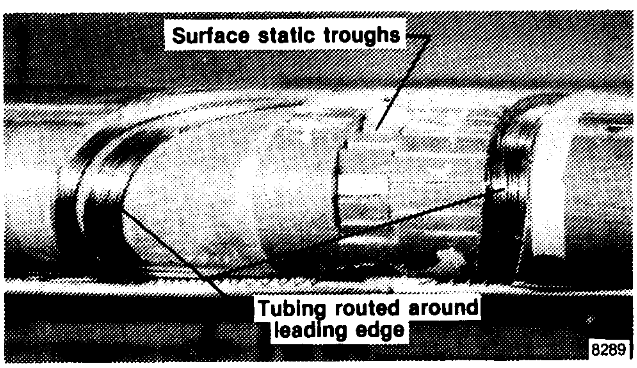

Fig. 12 Typical leading edge target cups.

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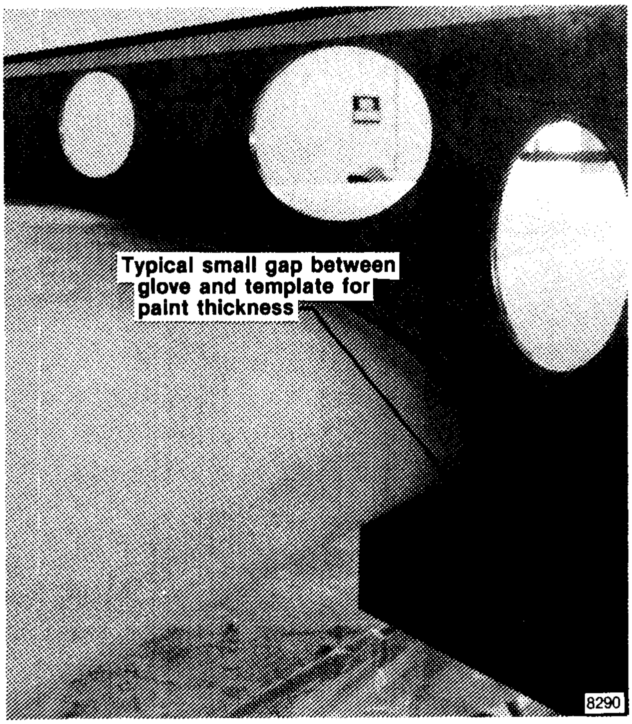

Fig. 13 Glove contour prior to paint application.

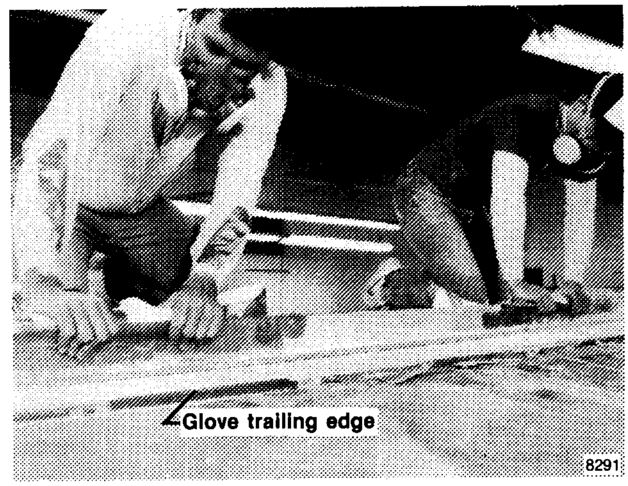

Fig. 14 Use of a spline board to contour the glove.

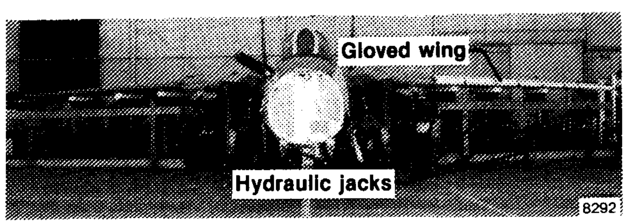

Fig 15 A 1-g load test after glove installation.

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Fig. 16 Electronic waviness gage and plotter.

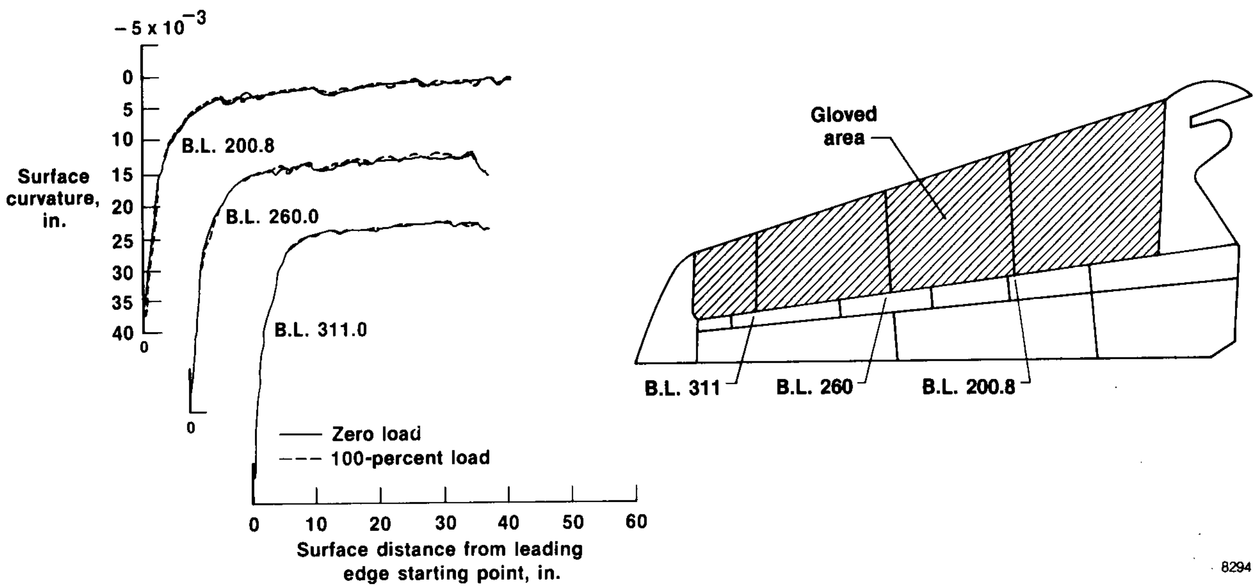

Fig. 17 Waviness measurements for glove I.

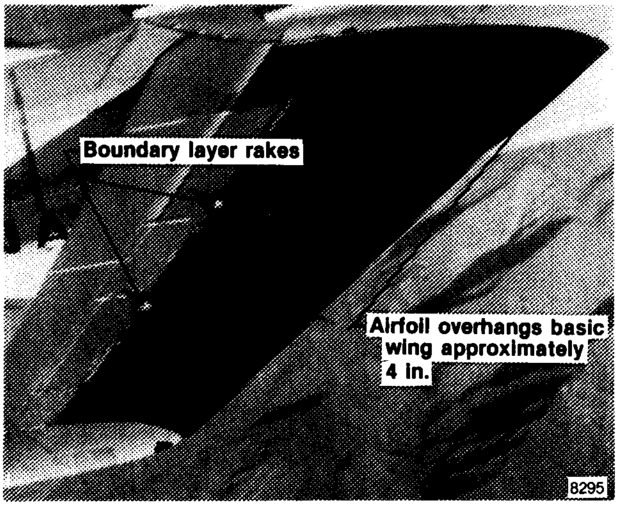

Fig. 18 F-14A right wing glove.

Fig. 19 F-15A right wing with glove installed.

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15. Supplementary Notes

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16. Abstract

Recently, two aircraft from the Dryden Flight Research Facility of NASA's Ames Research Center were used in the general study of natural laminar flow (NLF). The first, an F-14A aircraft on short-term loan to NASA from the U.S. Navy, was used to investigate transonic natural laminar flow. The second, an F-15A aircraft on long-term loan from the U.S. Air Force, was used to examine supersonic NLF. These tests were follow-on experiments to the NASA F-111 natural laminar flow experiment conducted in 1979. Both wings of the F-14A airplane were "gloved," in a two-phased experiment, with full-span (upper surface only) airfoil shapes constructed primarily of fiberglass, foam, and resin. A small section of the F-15A right wing was gloved in a similar manner.

Each glove incorporated provisions for instrumentation to measure surface pressure distributions. The F-14A gloves also had provisions for instrumentation to measure boundary layer profiles, acoustic environments, and surface pitot pressures.

Discussions of the techniques used to construct the gloves and to incorporate the required instrumentation are presented. Comparisons with the technique used to construct the F-111 NLF glove are made. Problem areas, with explanations and solutions when available, are addressed. Finally, an evaluation of the value and success of these techniques to modify airfoils is provided.

17. Key Words (Suggested by Author(s)) Flush surface pressure measurement; Gloved airfoils; Natural laminar flow	18. Distribution Statement Unclassified — Unlimited. Subject category 02

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