Overview of the DARPA/AFRL/NASA Smart Wing Program

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1. ABSTRACT

The DARPA/AFRL/NASA Smart Wing program, conducted by a team led by Northrop Grumman Corporation (NGC) under the DARPA Smart Materials and Structures initiative, addresses the development of smart technologies and demonstration of relevant concepts to improve the aerodynamic performance of military aircraft. This paper presents an overview of the smart wing program.

The program is divided into two distinct phases. Under Phase 1, (Jan 1995 - Feb 1999) the NGC team developed adaptive wing structures with integrated actuation mechanisms to replace standard hinged control surfaces and provide variable, optimal aerodynamic shapes for a variety of flight regimes. A smart wing 16% scale wind tunnel model, representative of an advanced military aircraft wing, was fabricated and tested in the NASA Langley Research Center (LaRC) Transonic Dynamics Tunnel (TDT) wind tunnel during two series of tests, conducted in May 1996 and June 1998, respectively. The smart wing model incorporated contoured, hingeless flap and aileron designs actuated using built-in SMA tendons. Control surface deflections of up to 10 degrees were obtained. Variable spanwise twist of the model was achieved using SMA torque tubes that employed novel connection mechanisms to effect a high degree of torque transfer to the structure. Up to 5 degrees of twist at the tip was demonstrated. Under steady-state conditions, performance improvements of 8-12% in comparison to a conventional design incorporating hinged control surfaces, over a broad range of wind tunnel and model test conditions, were established.

The paper summarizes the Phase 1 effort. Detailed discussions of the wind tunnel testing, model design and fabrication, and torque tube development, are presented in References 6-8. An important limitation of the Phase 1 effort, i.e., the limited band-width provided by the SMA based actuation mechanisms, is being addressed in Phase 2 by developing and validating hybrid concepts. Phase 2 research and development is focused on application of smart technologies to uninhabited air vehicles (UAVs) that (from a scaling standpoint), offer a higher near-term technology transition potential than their tactical aircraft counterparts. Phase 2 efforts are also discussed, albeit briefly, in the paper.

2. INTRODUCTION AND BACKGROUND

The theoretical benefits of active control of wing shape are well known and extensively documented[1-4]. For instance, hingeless contoured control surfaces provide improved aerodynamic performance. Deployment of conventional control surfaces in effect changes the overall wing camber but the rigid control surfaces give rise to discontinuous boundaries, resulting in early air flow separation, leading to reduced lift and increased drag. On the other hand, the use of smooth, continuous control surfaces delays the onset of flow separation and improves lift and stall angle characteristics. The focus of the smart wing program is to develop novel control surfaces (using smart materials and structures) to optimize aerodynamic performance in multiple flight regimes and ultimately enable the development of an aircraft wing with seamless control surfaces.

Under the smart wing Phase 1 program, three key features are being studied: (1) hingeless, smoothly contoured trailing edge (TE) control surfaces, (2) variable wing twist, and (3) use of fiber-optic pressure sensors to obtain real-time pressure distribution data. To evaluate the concepts and quantify performance improvements, two 16% scaled models (of a present generation fighter aircraft), one conventional and the other incorporating the above features (Figures 1 and 2), were

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fabricated and two series of wind tunnel tests were conducted, the first in May 1996 and the second in June 19… requirements and details of the first test are documented in Reference 5; this paper focuses on the second wind tu…

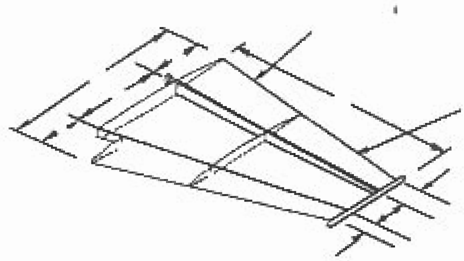


FIGURE 1. CONVENTIONAL WING MODEL

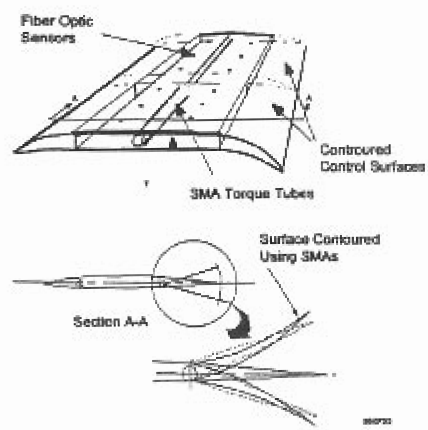


FIGURE 2. SMART WING MODEL

3. SUMMARY OF WIND TUNNEL TESTS

While the conventional model and the wing box structure for the smart wing model were retained from the first test, significant improvements in the torque tube design and the trailing edge control surfaces were implemented for the second test. Figure 3 shows the smart wing model and key components.

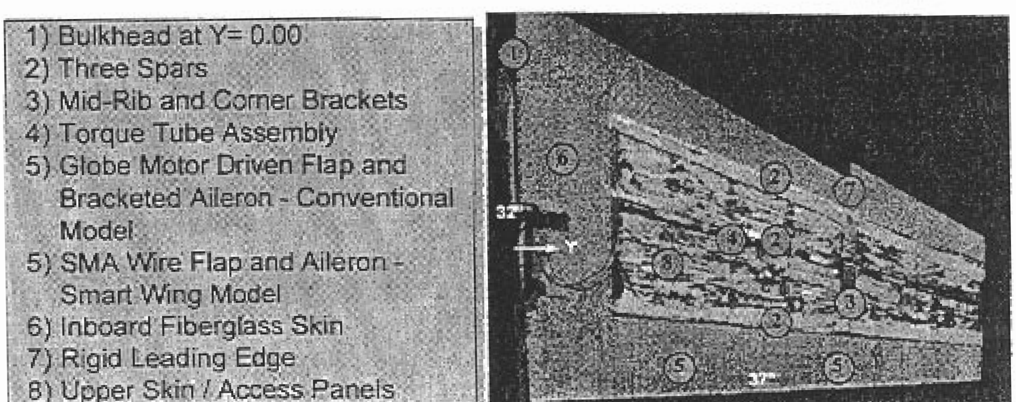
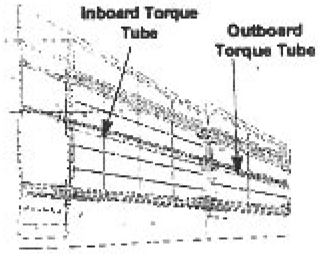


FIGURE 3. SMART WING WIND TUNNEL MODEL AND KEY COMPONENTS

3.1 Torque Tube Design

In the first wind tunnel test of the smart wing model, two torque tubes assemblies, one connecting the root rib to the center rib and the other connecting the center rib to the tip rib, were used. This required less torque from each of the SMA torque tubes but provided only 1.25 degrees of twist at the tip. After significant analytical model development and experimentation, an SMA torque tube with 1-inch diameter (the maximum dimension that could be accommodated in the model), which provided upwards of 3000 in-lbs of torque, was developed and used for the second test (Figure 4). This provided over 5 degrees of twist at the wing tip. Further details of the torque tube design and assembly procedure is described in a companion paper in this session[6].

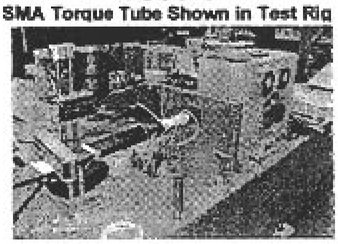
Test 1



- Two SMA Torque Tubes
- Inboard - 1" Dia., 1200 in-lbs Torque
- Outboard - 0.5" Dia., 600 in-lbs Torque
- Nicrome Wire Heater
- 1.25° Spanwise Twist Measured
- Twist Measurement Using NASA/LaRC Video Model Deformation System

Test 2

SMA Torque Tube Shown in Test Rig



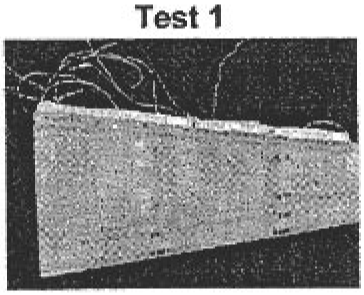
- One SMA Torque Tubes
- TT - 1.25" Diameter, 0.060" Wall Thickness 3600 in-lbs Output Torque
- Nicrome Wire Heater
- >5° Spanwise Twist Measured
- Electrolytic Tilt Sensor, MEMS Sensor, and NASA/LaRC Video Model Deformation System

FIGURE 4. TORQUE TUBE DESIGN AND IMPLEMENTATION FOR FIRST AND SECOND WIND TUNNEL TESTS

3.2 SMA Trailing Edge Control Surface Design

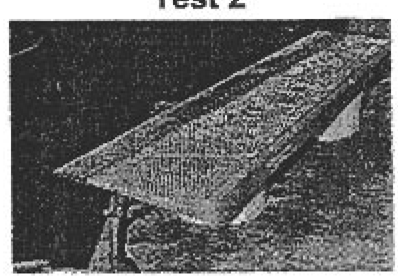
Similar to the first wind tunnel test, two hingeless control surfaces, a flap and an aileron, actuated using SMA wires embedded in the top and bottom facesheets, were developed. Improvements incorporated for this test included (Figure 5):

Test 1



- Binary SMA Wires
- RTV Core / RTV Facesheets
- TORLON® Trailing Edge Tip
- Deflection Measurement Using F/O and Foil Strain Gages

Test 2



- K-Alloy SMA Wires
- Aluminum FlexCore / RTV Facesheets
- AL Trailing Edge Tip
- Deflection Measurement Using Linear Potentiometer
- Increased Number Static Pressure Transducers

FIGURE 5. CONTROL SURFACE DESIGNS FOR FIRST AND SECOND WIND TUNNEL TESTS

- K-Alloy wires which provide increased workable strain
- Lightweight machined aluminum honeycomb core replacing heavier RTV core
- Increased spanwise shape control obtained by using three separate spanwise control sections on both the top and bottom facesheets
- LVDT displacement measurements transducers used for feedback control.

While these improvements allowed more uniform contouring and improved deflection control, the facesheets on the underside of the flap unexpectedly debonded during a high dynamic pressure (q), high angle-of-attack flutter clearance run, rendering the flap ineffective for the remainder of the testing. In spite of this setback, a large amount of data was obtained for various combinations of torque tube deflections, tunnel conditions, angles-of-attack and aileron deflections. (For all these data sets, the flap deflection was mechanically fixed at zero.) Details of the control surface design and performance in the tunnel are provided in Reference 7.

3.3 Summary of Wind Test Results

The models were tested at two different constant tunnel total pressures of 2200 psf (one atmosphere) and 1100 psf. Free stream dynamic pressures were set at 60, 90, and 120 psf, which provided Mach numbers ranging from 0.2 to 0.4. Data were recorded at angles-of-attack (AOA) ranging from -4 degrees to +16 degrees for various combinations of wing twist (0 to 5 degrees) and aileron deflections (0 to 10 degrees).

Baseline repeatability tests were conducted to ensure that both models had comparable behavior at zero control surface deflections and the results were valid for the entire range of experimental parameters. Because of the increased number of control channels, uniform and more accurate control of the spanwise deflection of the aileron could be achieved. Figure 6 shows the smart wing model with the maximum aileron deflection in the tunnel.

Significant improvements in rolling moment were recorded for the smart wing model in comparison to the conventional model. For instance, at 8 degrees AOA, a 10% increase in the rolling moment coefficient was obtained with the smart aileron versus conventional with 10 degrees of deflection for both. Similar results were obtained at all the test conditions and are discussed in detail in Reference 8. Figure 7 shows the improvements in the pressure distribution near the trailing edge resulting from eliminating the slope discontinuity exhibited by conventional control surfaces. Highlights of the test results (including selected results from test 1) are given in Figure 8. The percent improvements shown are typical, and do not necessarily represent maximum or minimum values.

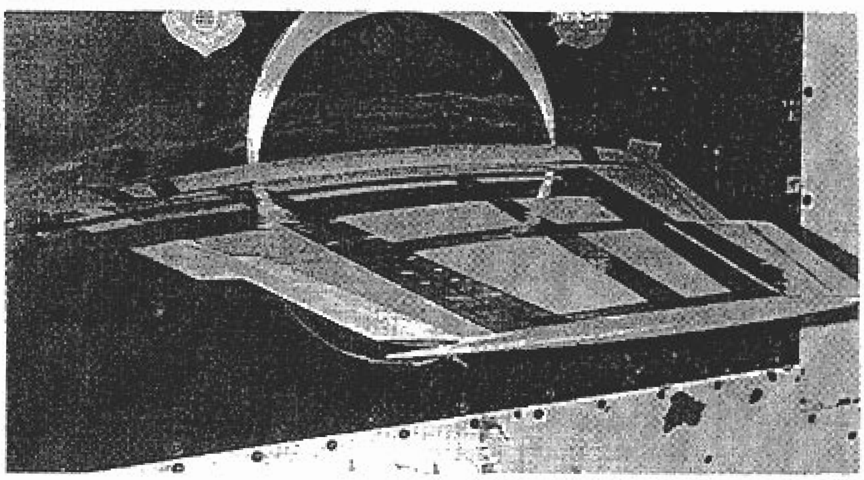


FIGURE 6. SMA AILERON DEFLECTED 10 DEGREES

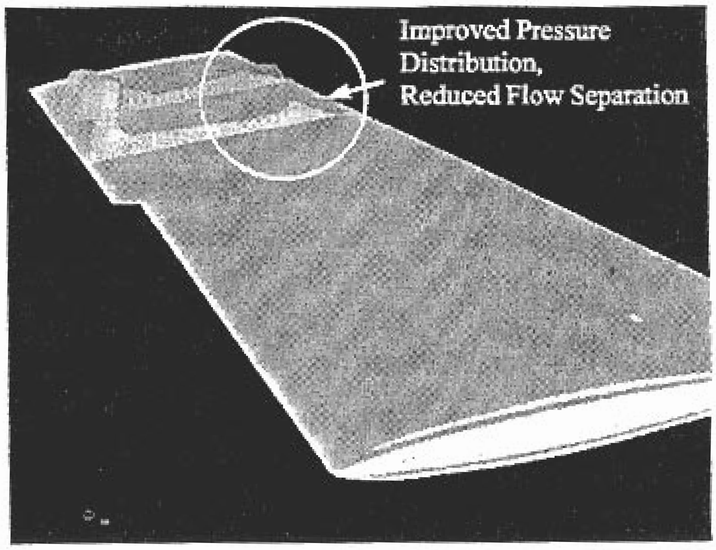


FIGURE 7. IMPROVED PRESSURE DISTRIBUTION OBTAINED FROM CONTOURED, HINGELESS AILERON DESIGN

Configuration	Deflection or Wing Twist (Deg)	Lift ΔC_L	Roll ΔC_l	% Improvements Lift	% Improvements Roll
Flap Only (Test 1)	7.5	0.058	0.019	9.7%	10.2%
Flap and Aileron Combined (Test 1)	7.5	0.092	0.039	17.6%	17.1%
Aileron Only (Test1)	5		0.015		8.0%
Aileron Only (Test 2)	10		0.019		10.5%
Wing Twist (Test 2)	3 5	0.034 0.05	0.019 0.03	8.0% 11.5%	10.0% 15.6%
Wing Twist (Test 1)	1.4	0.041	0.022	10.0%	12.8%
Combined Aileron & Wing Twist	+10° Aileron, +4.5° Wing Twist	0.057	0.031	15.3%	17.3%

Angle of Attack = 8 Degrees

FIGURE 8. SUMMARY OF TYPICAL RESULTS - TESTS 1 AND 2

For the torque tube results, the measured test deflections were consistent with analytical predictions and the maximum tip twist of 5 degrees was markedly higher than the 1.25 degrees obtained in the first test. In fact, to the authors' knowledge, the SMA torque tube developed for this test has the highest torque capacity of any currently available SMA torque tube and represents a significant improvement in the state-of-the-art. However, because the inboard section of the wing is significantly stiffer than the outboard section, the spanwise twist was non-uniform compared to the first test, with much of the twisting concentrated towards the tip. Hence little overall performance improvements resulted from the higher twist angle compared to the first test. Details are presented in References 7 and 8.

4. PHASE 2 PLANS

For the Phase 2 effort, the wing model has been changed to a Northrop Grumman uninhabited combat aircraft design for several reasons:

- The subsonic aircraft has thicker wings, making it easier to incorporate the actuation system
- The smaller overall size enables a larger scale (30% vs. 16% for Phase 1) model to be tested
- Technology transition would be cost-effective and easier for an uninhabited aircraft.

An important limitation of the Phase 1 effort is the bandwidth achievable using SMA-based actuation. The current design takes several seconds to deploy and almost twice that time to be returned to neutral position (relying on passive cooling due to the airflow). Even if active cooling designs are developed, the maximum bandwidth achievable would be one or two Hertz, making it unsuitable for active maneuver control of operational aircraft. Hence, a significant portion of the Phase 2 effort is dedicated to improving the control surface actuation bandwidth. Several hybrid designs using combinations of SMA, piezo-electric materials, and electro-rheological materials are being developed. Two wind tunnel tests planned for Oct 1999 and Sep 2000 will address static and dynamic actuation, respectively. For both tests, full-span models, rather than the half-span designs tested in Phase 1, will be used.

5. CONCLUDING REMARKS

Work done to date on the smart wing program provides quantitative data on performance improvements that could be achieved by novel control mechanisms such as smoothly contoured, hingeless control surfaces and actively controlled wing twist. These results are significant because similar improvements can be realized on full-scale aircraft if issues related to power supplies, cost, system reliability and overall system integration, can be resolved. Phase 1 accomplishments, in terms of the technical challenges encountered and addressed, as well as the knowledge gained through the design, fabrication, and test experience, provides a strong foundation for the Phase 2 program.

Several of the above issues and important limitations encountered in Phase 1, such as low actuation bandwidth, restricted range of deflections, and limited number and range of test parameters, are being addressed in Phase 2. At the end of Phase 2, the technology readiness level is expected to be significantly higher and perhaps sufficient to perform flight testing and paving the way for the eventual development of a revolutionary "smart air vehicle."

6. ACKNOWLEDGEMENTS

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Besides the authors, key members of the smart wing development team at Northrop Grumman include Mr. Allen Lockyer (system integration), Mr. Larry Jasmin (hardware design), Dr. Kari Appa and Mr. Dave Cowan (aeroelastic analysis), and Mr. John Flanagan (model fabrication). Other members of the team include Dr. Bernie Carpenter of Lockheed Martin (SMA control surface development), and Mr. Mark West, Mission Research Corporation (system software and test support).

The above listed participants, and other members of the smart wing program with complementary skills in diverse areas of expertise, constitute a well-knit team formed over several years. Such a multidisciplinary ensemble, combining the resources of government, industry, and academia, was the key to achieving the considerable accomplishments of the current program, and would be indispensable for the eventual development of a smart air vehicle.

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