



Low and High-Speed Cryogenic Testing of a Wind Tunnel Model with Remote Control Actuation (RCA)

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Traditional wind tunnel testing dictates the fabrication and testing of numerous fixed parts requiring time consuming model changes to test multiple configurations of interest. Remotely actuated components using hydraulic or electric actuators are commonly used in many wind tunnel model designs to increase productivity; however, they have not been shown to be a viable solution for cryogenic wind tunnel testing. Utilizing remotely controlled actuation (RCA) of shape memory alloy (SMA) based actuators has shown to be a viable solution to replace fixed wind tunnel parts with instrumented components able to controllably, accurately and repeatably move to a fixed position under all conditions experienced within a typical high-speed or high-lift test campaign, without tunnel access, thus enabling a significant increase in productivity, improved data quality, and reduced cost of wind tunnel testing while acquiring flight Re data early in the development cycle. An international team from Boeing, Deharde, the European Transonic Windtunnel, and NASA developed and repeatedly tested two 2D RCA airfoils between 2014 and 2018 with controllable surfaces to demonstrate and assess the maturity of this technology. The airfoils incorporated a suite of sensors, including pressure taps, thermocouples, control surface position sensors, and strain gages for load sensing. Next steps include integration and test of multiple RCA elements within a 4.5% 787 semi-span production model. RCA spoiler test article design, testing, and resulting analysis is presented along with the successes, challenges, maturity levels and future of this innovative technology.

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I. Nomenclature

2D	=	2-dimensional, in the context of a wind tunnel model fully spanning the WT test section
BR&T	=	Boeing Research & Technology
CFD	=	Computational Fluid Dynamics
ETW	=	European Transonic Windtunnel (Cologne, Germany)
Fe	=	iron
GN	=	gaseous nitrogen
ID	=	internal diameter
in-lbs	=	inch-pounds
LaRC	=	NASA Langley Research Center
LN	=	liquid nitrogen
LuFo	=	Federal Aviation Research Program (Germany)
M	=	Mach number
NiTi	=	Nickle-Titanium metal alloy
NiTiHf	=	Nickle-Titanium-Hafnium ternary alloy
NTF	=	National Transonic Facility (Hampton, VA, USA)
OD	=	outer diameter
PETW	=	Pilot European Transonic Windtunnel (Cologne, Germany)
psf	=	pounds per square foot
Q	=	dynamic pressure, psf
Re	=	Reynolds number
RTD	=	resistance temperature detector
SMA	=	Shape Memory Alloy
RCA	=	Remotely Controlled Actuation
SMARCA	=	Shape Memory Alloy Remote Control Actuation
TCT	=	Transonic Cryogenic Tunnel (NASA-Langley)
TRL	=	technology readiness level
VG	=	vortex generator
WT	=	wind tunnel
C_p	=	pressure coefficient

II. Introduction

Testing in high pressure cryogenic wind tunnels is highly desirable due to the ability of such tunnels to obtain aerodynamic, aeroelastic and loads data representative of flight conditions with a sub-scale model early in a typical all-new commercial aircraft development program. However, due to the high cost and challenges of testing in such facilities [1], the primary sources of aerodynamic wind tunnel data during the product development phase are obtained at low/medium Re number, along with the growing reliance on CFD, coupled with past experience with similar aircraft configurations, enabling a fairly accurate extrapolation to flight for much of the flight envelope [2], [3], [4]. However, even with the decades of airplane design experience and increasingly sophisticated high-fidelity computational tools, aircraft programs continue to experience aerodynamic surprises during flight testing [5][+many others!]. This paper discusses the systematic advances made using remotely controlled shape memory actuators via a multi-year collaborative effort, showing tremendous progress towards enabling a significant reduction in the cost of cryogenic wind tunnel testing.

Cryogenic pressurized wind tunnels are expensive to use due to the use of liquid nitrogen (LN), gaseous nitrogen (GN), a very wide range in temperatures, circuit pressurization, dry air / GN conditioning time, highly accurate wind tunnel models and very long model change times. Every model change requires the test section and model to be conditioned for safe access prior to a hands-on model change. Each model access introduces the risk of liquid contamination to the extremely dry test environment, required for frost-free testing. The desire for remotely controlled configuration changes then is clear: a technology which enables remote configuration changes while not requiring tunnel access would result in increased testing productivity and data quality, thereby reducing testing costs and increasing the amount of high Re data acquired. The belief is that with this new capability, customer testing at flight Re earlier in a program becomes much more likely, good for both the customer and the tunnel. Shape memory alloy

technology provides a compact, powerful, and accurate remote actuation capability for instrumented model parts in the wind tunnel environment. This technology is being matured by Boeing and demonstrated for a variety of applications, including ecoDemonstrator flight testing of wing control surfaces [6], [7], VGs and more. Simple SMA rotary and linear actuators can be integrated into a wind tunnel model enabling efficient remote actuation [8].

III. Background

The Boeing / Deharde / ETW RCA team conducted the first active wind tunnel model test under cryogenic conditions at the PETW in December 2014 as part of the Boeing-German Government's *Federal Aviation Research Program* (LuFo) cooperative program. The original test article was a representatively scaled 2-dimensional wing with a simple flap controlled by an integrated SMA rotary actuator. The test article was modified to improve performance and then tested at the NASA Langley 0.3m Transonic Cryogenic Tunnel (TCT) in September 2016 as part of the Boeing-NASA Shape Memory Alloy Remote Control Actuation (SMARCA) project. Testing was conducted in multiple phases to systematically demonstrate the technology readiness level (TRL) and maturity [9], [10]; system capabilities, limitations, and operational features of the actuation system.

- Phase 1 explored the system capability with changing pressure, temperature, and Mach number.
- Phase 2 demonstrated a future cryogenic test paradigm with the active surface moving 29 times in 3 hours at high and low speed flows, varying pressures up to 2800 psf, and from +100 °F (+38 °C) down to -250 °F (-150 °C), **without accessing the model**.

The primary objectives of the simple flap demonstration tests were as follows:

- Demonstrate remotely controllable flap settings under tunnel operational extreme temperatures and loads and acquire relevant data;
- Demonstrate flap move between -5 deg to +45 deg under low speed conditions (up to 400 psf, M=0.3);
- Demonstrate flap move between -5 deg to +15 deg under high speed conditions (up to 2800 psf, M=0.7);
- Demonstrate open and closed loop architectures with positional and temperature feedback;
- Demonstrate an integrated, packaged SMA actuator system solution for a cryogenic environment;
- Validate viability with an RCA/SMA system while documenting lessons learned for further study;
- Assess TRL level / level of maturity for each application.

This series of tests demonstrated the efficacy of the RCA simple flap concept for 2D cryogenic wind tunnel models, with TRL levels between 5-7 generally established throughout the test envelope.

Following the successful proof of concept testing of the simple flap 2D configuration, a new test article based on a representatively scaled inboard spoiler wing section was conceived for the next series of tests building off the successes and lessons learned. The goal of the 2016-2017 program was a continuation of the earlier campaigns: to demonstrate that a more complex & heavily instrumented SMA actuation system could be integrated into a 2D wind tunnel model to remotely and accurately deploy and control a spoiler, collect data while being tested within cryogenic wind tunnels under typical high-speed and low-speed testing envelopes - without removing the model from the tunnel. The wind tunnel tests were designed to validate that the spoiler could be moved and controlled under maximum and minimum temperatures and loads while acquiring aerodynamic, thermal, sensor and model positional data within stated accuracy, precision and repeatability target levels. Other objectives for the spoiler-based 2D model were to:

- Generate aerodynamic data on spoiler performance;
- Demonstrate feedback position and temperature control of spoiler;
- Demonstrate new system architecture;
- Implement a spoiler brake;
- Use magnetic restoring force to move spoiler to faired position;
- Capture spoiler thermal data for future RCA cryogenic designs;
- Assess spoiler angle & torque accuracy requirements;
- Assess TRL level / level of maturity for each application.

The target accuracy requirement for each flap or spoiler setting was ± 0.1 degrees. More detailed requirements will be described in Section IV.

IV. Remote Control Actuation Test Articles

The RCA systems are based on Boeing's Shape Memory Alloy actuator technology developed for a range of applications: e.g. aircraft wing / body, control surfaces, and nacelles to missiles and valves [11], [12], [13], [14]. Shape Memory Alloys are active metallic materials that convert thermal energy into mechanical energy. Heating the material above its Austenitic transition temperature activates a crystalline structural phase change causing the material to revert to a previously "remembered" "hot" shape. When cooled below the transition temperature the SMA transforms into its more compliant (lower modulus) "cold" Martensitic form. It can be easily deformed when a load is applied during transition from Austenite to Martensite or when in the final Martensite state. SMA can also exhibit a two-way shape memory effect which results in a "remembered" Martensitic form as well as the Austenitic form. SMA tubes are a natural and efficient form for generating rotary output, Figure 1. Such tubes can be engineered to twist when thermally cycled creating a solid state high-torque rotary actuator. The simplest mode of operation is to have one end fixed while the other end provides rotary output. The output torque increases with tube diameter and thickness. The longer the tube the greater the output twist. When designed for actuation these tubes are usually thick-walled, with the ratio of inner to outer diameter of 0.8 to 0.6. The ends of the tubes are generally splined or pinned. Boeing has designed, built, and tested tubes with a large range of outputs, including in the range useful for wind tunnel models tested at low and high-speed conditions. Boeing has also successfully employed tubes made of equiatomic NiTi, Nickel rich NiTi, and ternary alloy NiTiHf.

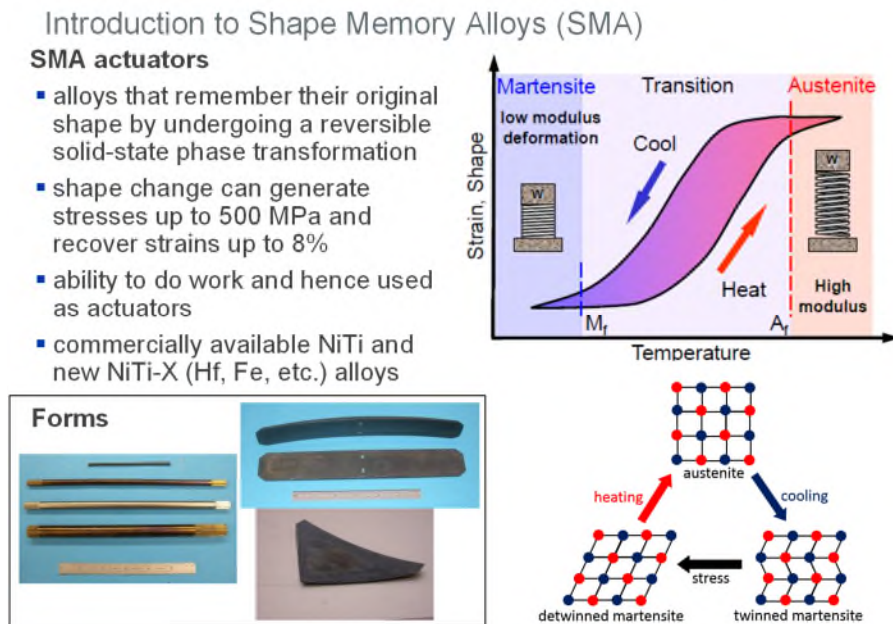


Fig. 1 Shape Memory Alloy "101" - background

The SMA actuation systems include five main components: NiTi tubes trained as rotary actuators, sensors, control and power electronics, control law, and supporting mechanisms. The rotary actuator elements are tubes made from high temperature (above 90 °C) equiatomic nickel titanium material. These tubes, which range in size from 0.2-0.375" OD, are trained by repeated thermomechanical cycles to provide up to 5% controllable shear strain. A 3-5" long tube can provide over 90° rotation at 100-400 in-lbs of torque depending on the outer diameter and wall thickness. Sensors are used to measure the control surface position and loading, and SMA element temperature and include magnetic position sensors, strain gages, RTDs. The control system is incorporated into a microprocessor with data acquisition and power output capabilities. A modern control law is built around a plant model of the NiTi tube, thermal models

of the SMA element and structure, and models of additional mechanisms, connections, and associated sensors. The attachment of the tubes to the structure and control surface is a critical part of the design. Mechanisms provide additional capability such as locking, braking, pinning, and torque-limiting.

Two test articles will be described below: a 2D airfoil with an RCA aileron and a different 2D airfoil with an RCA inboard spoiler. The 2D airfoil with the RCA inboard spoiler will be described in greater detail to support discussion of the test results in the next section.

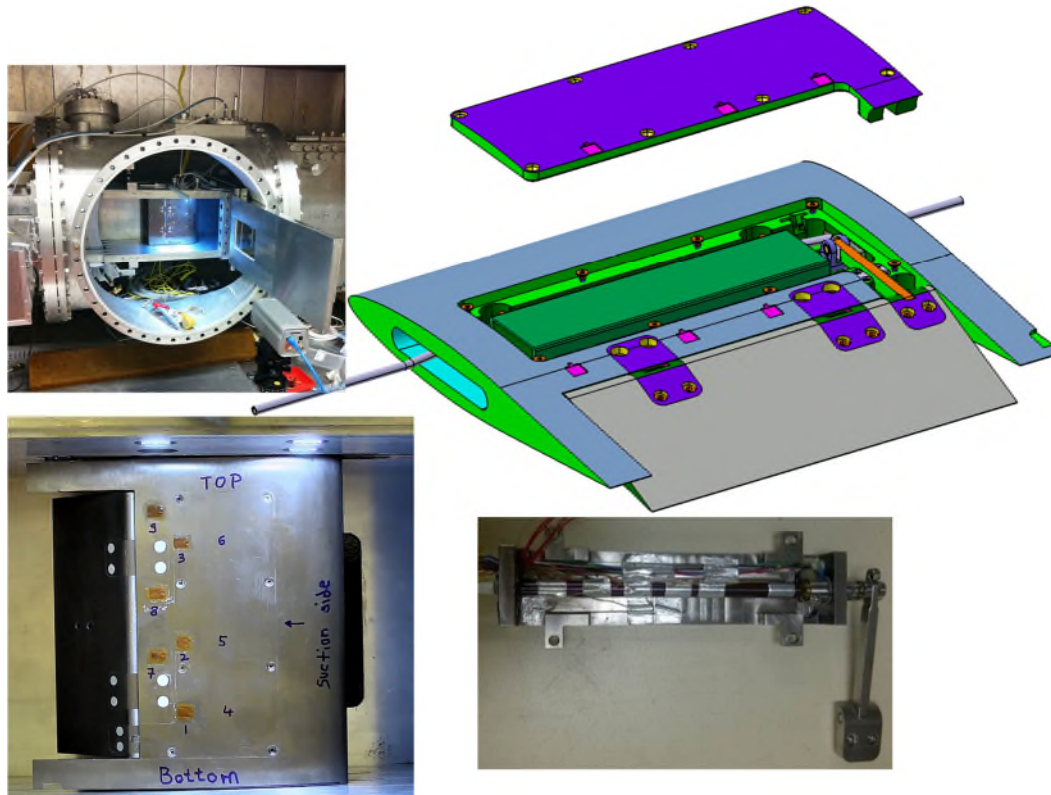


Fig. 2 RCA Aileron Test article and components in Pilot European Transonic Windtunnel test article

The 2D RCA aileron test article, shown above in Figure 2, was originally designed and tested for a Pilot European Transonic Windtunnel (PETW) kickoff test in December 2014, subsequently updated during lab testing in 2015-2016, and followed by additional testing at the PETW and NASA Langley TCT in 2017. The test article is a symmetric NACA 65-0012 airfoil with a controllable aileron flap with a 9" constant chord and 9.5" span, including the tunnel interface. The aileron-type flap has a 3.3" constant chord with a range of motion of -15 degrees trailing edge up to +45 degrees trailing edge down. The actuation system to drive the flap is based on the BR&T SMA torsional actuator technology. The major components of the actuation system include: the SMA torsional actuator, 4-bar linkage, actuator twist output magnetic encoder, and torque measurement via strain gages. The NiTi actuation tube element, with an OD 0.375", ID 0.225" and length of 5.7" (5" active length), was engineered for rotary motion and provided torque output of 375 in-lbs. One of the primary advantages of the NiTi tube technology is the efficient integration of the system into a wing body. The airfoil, flap, and actuation system components were fabricated using wind tunnel model best practices by Deharde Maschinenbau. Boeing fabricated and trained the SMA tube based on best practices.

The updated 2D airfoil used with the RCA inboard spoiler, Figure 3, was designed incorporating the lessons learned from the first 2D airfoil. The detailed requirements for the actuation system, more expansive than for the aileron model, are shown in Table 1. This airfoil is based on a representative truncated airfoil shape at an inboard spoiler location for a 4.5% half model of a wide body transport aircraft (787-8). The second airfoil incorporates an SMA rotary actuator to drive the spoiler and an SMA linear actuator to drive a brake element. The RCA system includes three methods to hold the spoiler position: (1) feedback control using temperature of the SMA rotary actuator

or spoiler position, (2) a friction brake set to hold when deactivated and (3) a manually set mechanical pinned connection. The spoiler airfoil was designed to incorporate a suite of sensors, including pressure taps, thermocouples, spoiler position sensors, and strain gages for load sensing, among others. The SMA element was heated with an internal cartridge heater and an external guard heater at each end. Together these heaters allowed the operator to uniformly heat the SMA element. In addition, a magnetic return element was built into the airfoil surface to provide restoring force to help return the spoiler to the faired position.

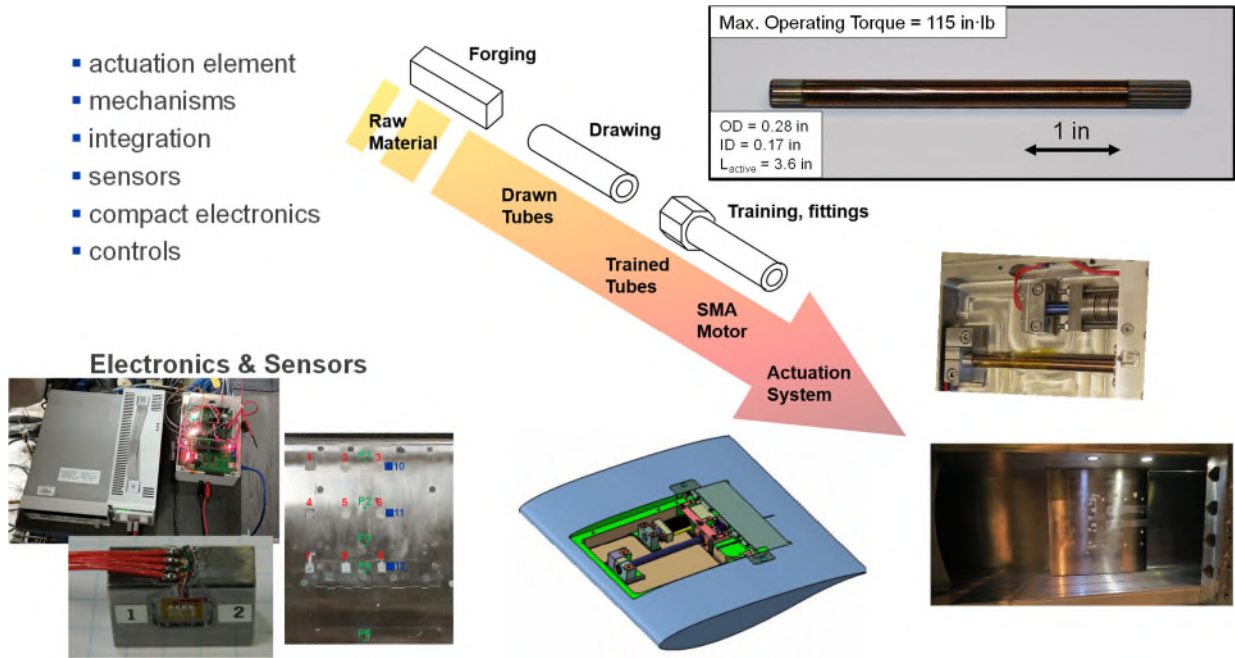


Fig. 3 2D Remote Control Actuation inboard spoiler system components

Table 1: RCA Spoiler Requirements

High Speed	Low Speed	Spoiler Accuracy	Measurements	System accuracy	Other Features
<ul style="list-style-type: none"> ▪ 0- 20° ▪ Max Torque 25 in-lbf ▪ Min Torque - 15.56 in-lbf 	<ul style="list-style-type: none"> ▪ 0- 60° ▪ Max Torque 22.16 in-lbf ▪ Min Torque -2.93 in-lbf 	<ul style="list-style-type: none"> ▪ ±0.1 deg. 	<ul style="list-style-type: none"> ▪ Torque at SMA ▪ Torque at spoiler ▪ Spoiler angle ▪ Temperatures: int. & external ▪ Closed loop control 	<ul style="list-style-type: none"> ▪ Repeatability independent of loading ▪ Auto-mode ▪ Limit temp leakage 	<ul style="list-style-type: none"> ▪ Brake system ▪ Pressure ports ▪ Assist to fair Spoiler ▪ Boeing SMA best practices

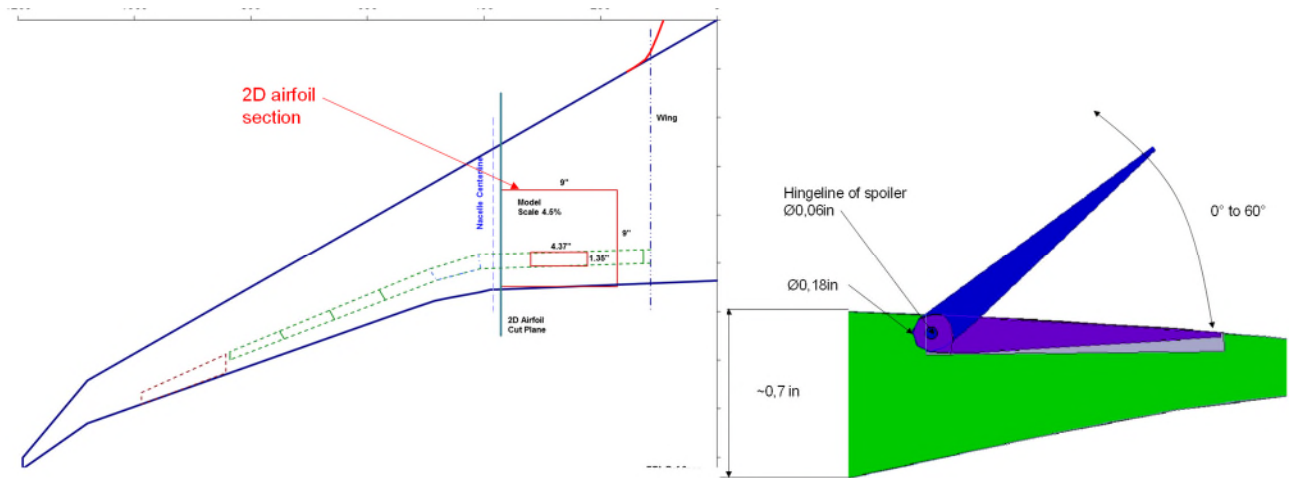


Fig. 4 2D airfoil with RCA spoiler planform based on 4.5% wide-body wing and cross-section

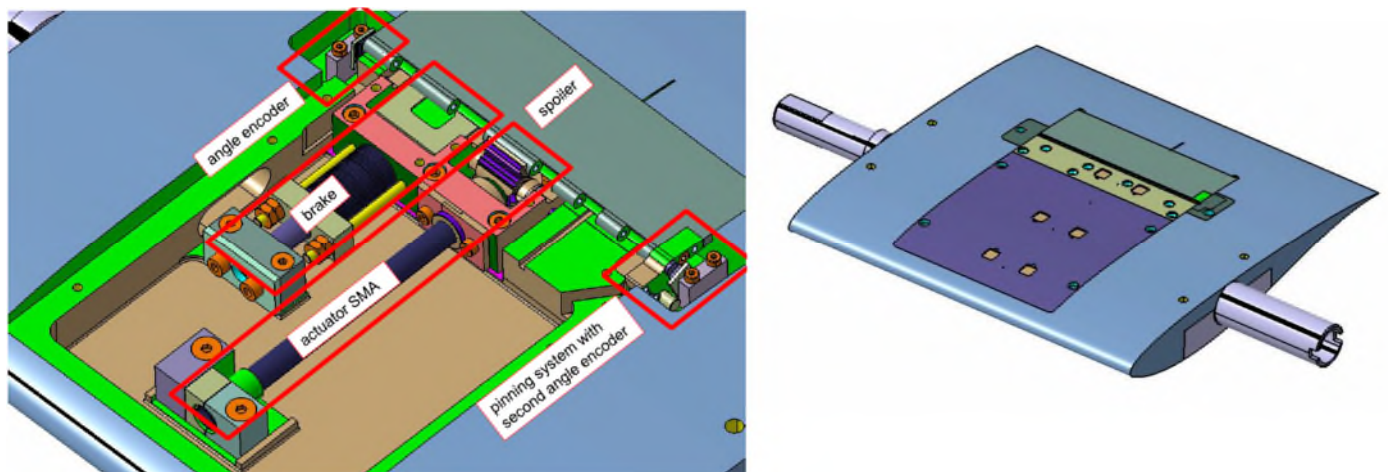


Fig. 5 RCA spoiler actuation components and assembly

Figure 4 shows the relative location and basic requirements upon which the design of the 2D airfoil with spoiler was based. The spoiler airfoil and actuation system components were built by Deharde, with the SMA actuator and brake elements fabricated by Boeing Research and Technology. The spoiler internal components and the assembled airfoil are shown schematically in Figure 5. The spoiler system subcomponents were extensively tested in the laboratory and in a cryogenic chamber prior to the system assembly into the airfoil. Figure 6 shows the disassembled subcomponents being tested in a laboratory environment. Finally, the completed system was tested in a static cryogenic chamber prior to testing in PETW. These tests demonstrated the system operation viability within the complete testing envelope along with the performance of subcomponents such as sensors, control system, brake, drive train, and magnet return element.

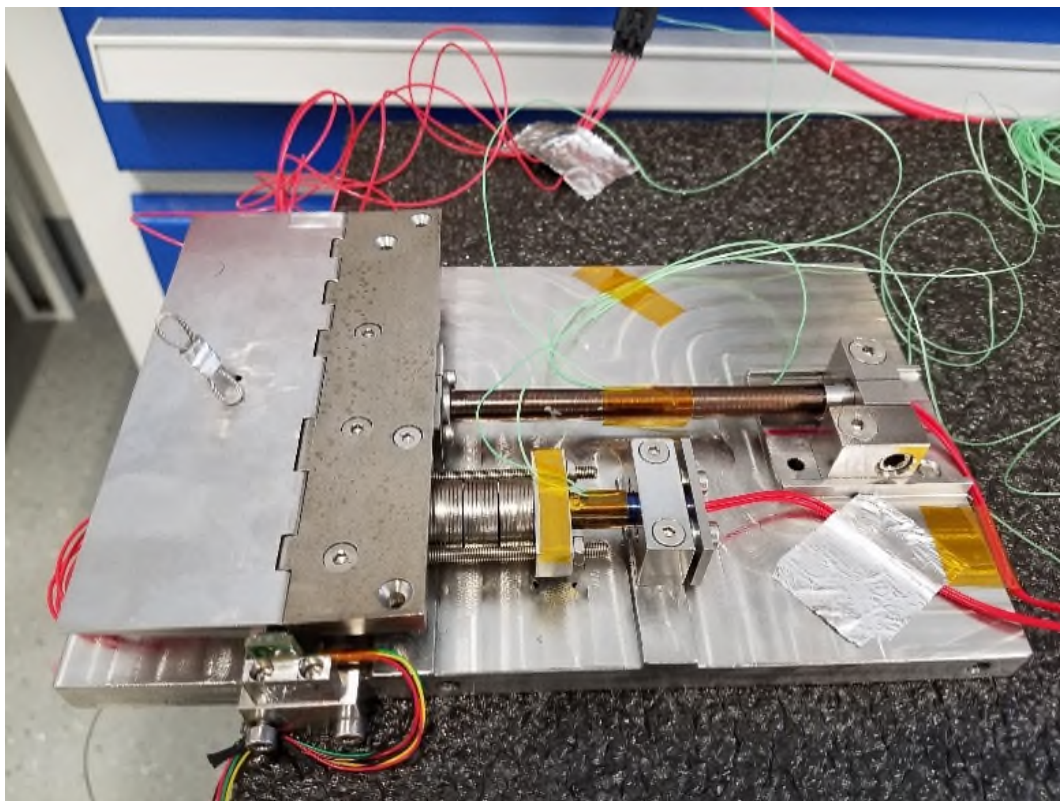


Fig. 6 SMA actuated spoiler and brake component test

V. Wind tunnel test results

The primary goal of these tests was to mature remote actuation technology of wind tunnel models for testing under cryogenic, high load and low-to-high speed conditions to demonstrate the increase in testing productivity and data quality while reducing costs. Each following test, whether at PETW or TCT, included improvements discovered in the previous test; thus, the test facilities were in turn highly complementary to the success of this program.

The wind tunnel test results in this section will focus on the most recent 2D RCA spoiler testing. This test article was tested in both the PETW and TCT tunnels. The primary objective was to demonstrate that the spoiler moved controllably at maximum and minimum temperatures and loads. Thus, it was important to hit the corners of the testing envelope representative of production high speed and low speed testing. The testing needed to demonstrate collection of data with changing configurations under high speed and low speed conditions without requiring access to the model. In addition, hinge-moment acquisition was desirable on the spoiler while simultaneously moving the control surface or tunnel conditions. Testing at the two tunnels enabled the team to fix problems and iteratively improve the RCA capability, the spoiler accuracy and speed reaching a commanded position using position feedback control.

Three test methods were identified:

- (1) constant wind tunnel condition while varying control surface angle
- (2) change wind tunnel condition while holding at constant control surface angle
- (3) collect data after under full cold soaked conditions then move control surface

The test article was tested extensively on the bench and in a cryogenic chamber under representative loads, Figure 7, to verify that the system worked as designed and to calibrate the system instrumentation. Functional checks that could be repeated during the wind tunnel tests were developed and used to provide a baseline system performance. The cryogenic chamber test also verified the correct synchronization of the brake and spoiler drive actuators.

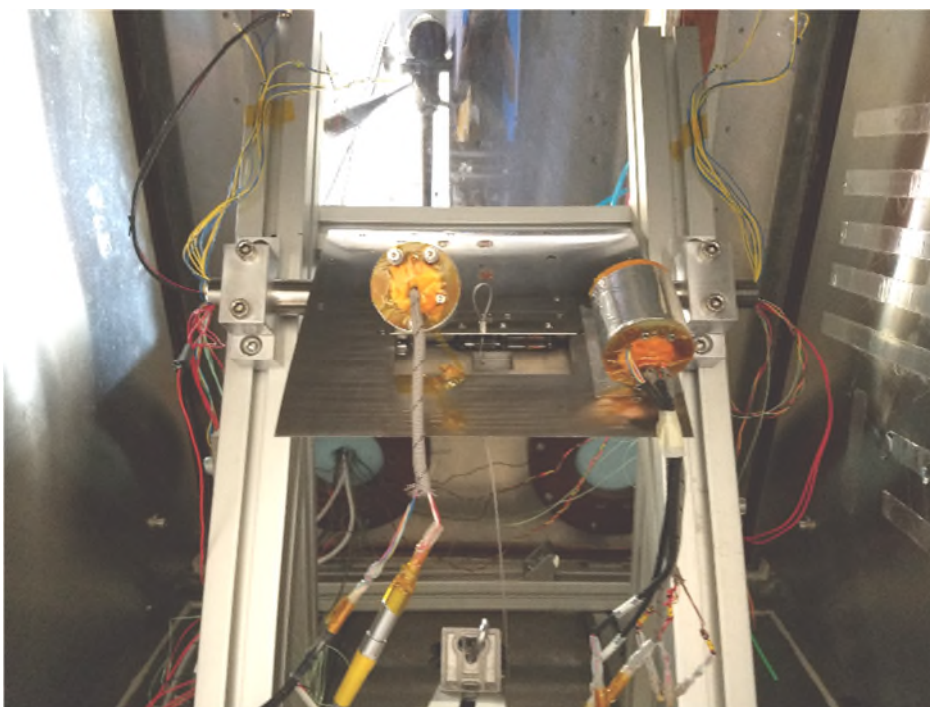


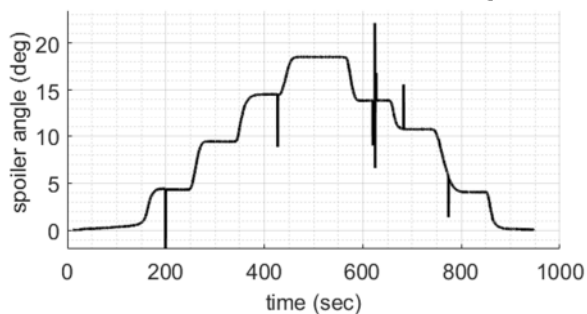
Fig. 7 2D RCA Spoiler test article in a cryogenic chamber at PETW

The objectives were accomplished by defining and completing a series of test conditions divided into 2 Phases. Phase 1 was focused on exploring system performance as a function of temperature, q , and Mach. Phase 2 was an operational demonstration consisting of position changes at multiple tunnel conditions, again as a function of temperature, q and Mach). Phase 2 demonstrated the unique ability to control a cryogenic wind tunnel model control surface while allowing multiple model configurations and tunnel conditions to be tested without the need for human access to make model changes.

Figure 8 shows the results of two runs, angle increment and continuous sweep, during Phase 1 at PETW. The plot on the left taken under high speed conditions ($T = -100\text{ }^{\circ}\text{C}$, Mach 0.7, $Q=1343\text{ psf}$) with the spoiler moving from 0 (faired) to 20 degrees deflection and back to 0 degrees in 5-degree increments. The plot on the right-hand side of Figure 8 shows the spoiler angle versus time during a continuous sweep at low speed conditions ($T=-150\text{ }^{\circ}\text{C}$, Mach=0.3, $Q= 300\text{ psf}$). The noise (vertical transients) seen in the data was a result of the electronics sensitivity to the cryogenic conditions. This problem was fixed for the next test sequence. During Phase 2 testing the spoiler system performed well at all tunnel conditions from -150°C to 22°C at low speed (“low speed” defined as roughly Mach = 0.3; q up to 400 psf) and high speed (“high speed” defined roughly as Mach up to 0.8 and dynamic pressures up to 2800 psf) and included moving the spoiler over 50 times in 7 hours without tunnel access.

Angle Increments

$T = -100\text{ C}$; Mach = 0.7; $Q = 1343\text{ psf}$



Continuous Sweep

$T = -150\text{ C}$; Mach = 0.3; $Q = 300\text{ psf}$

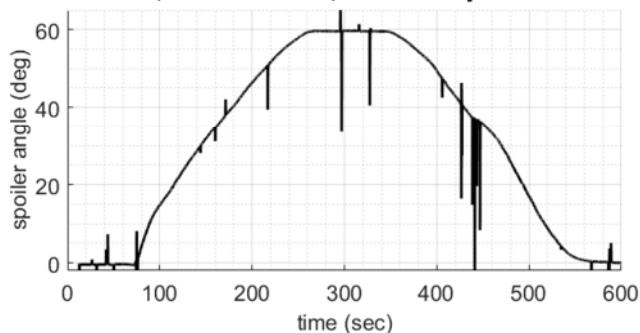


Fig. 8 Two test methods for 2D RCA spoiler, angle increment (left) at high speed conditions and continuous sweep (right) at low speed conditions, plotted as spoiler angle versus time.

The aerodynamic performance of the system was evaluated with four pressure ports as shown in Figure 9. These data were taken during the Phase 2 evaluation at high speed conditions ($T = -100\text{ }^{\circ}\text{C}$, Mach 0.7, $q = 829\text{ psf}$).

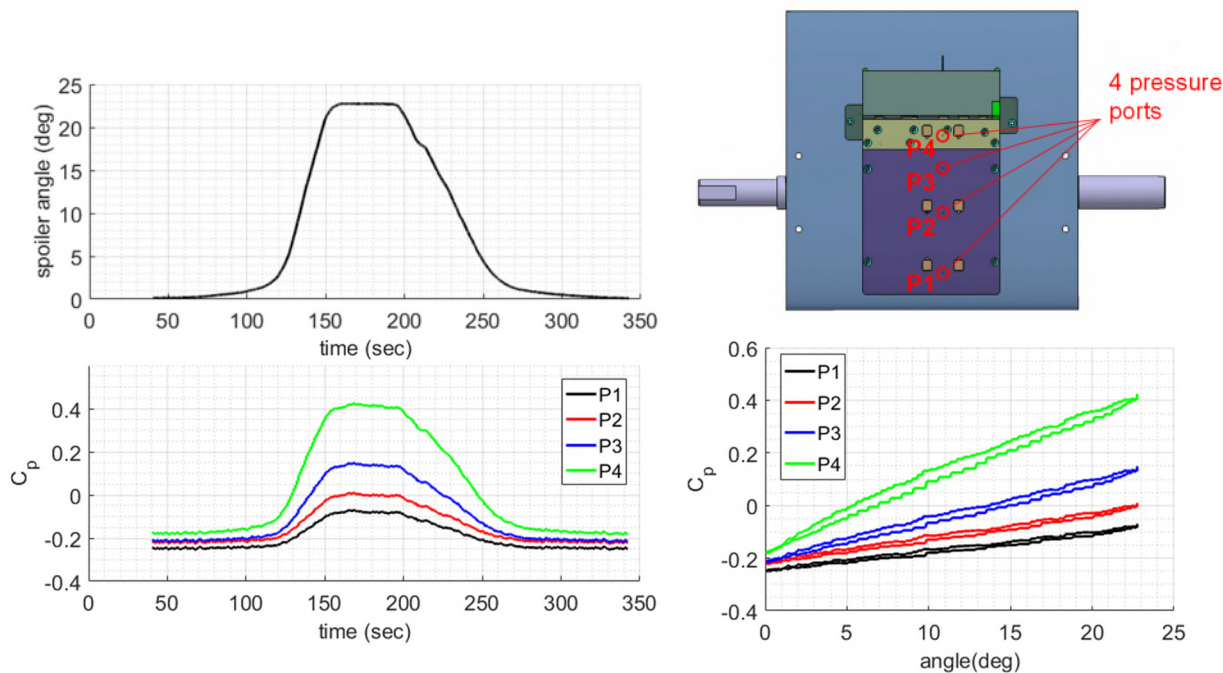


Fig. 9: Continuous sweep of the RCA spoiler at high speed conditions ($T=-100\text{ }^{\circ}\text{C}$, Mach = 0.7, and $Q=829\text{ psf}$) and associated pressure coefficient data.

The Phase 2 testing at TCT demonstrated that the test article could be controlled to allow numerous test points and configuration changes without accessing the tunnel. It was parsed into three temperature ranges: $+22\text{ }^{\circ}\text{C}$, $-100\text{ }^{\circ}\text{C}$, and $-150\text{ }^{\circ}\text{C}$ and 13 separate tunnel conditions ranging from 0.25 Mach to 0.7 Mach and 250 psf to 1700 psf. The spoiler made 53 controlled steps and 2 continuous sweeps during this 3-day testing without having to access the model. Traditional testing would have required three manual model changes (model access), thereby decreasing wind-on productivity significantly while allowing for possible liquid contamination. The average error between commanded and actual spoiler position was 0.11 degrees, which was within 0.01° of pre-test tolerance objectives. Figure 10 shows the complete Phase 2 test sequence successfully demonstrating a new cryogenic wind tunnel testing paradigm.

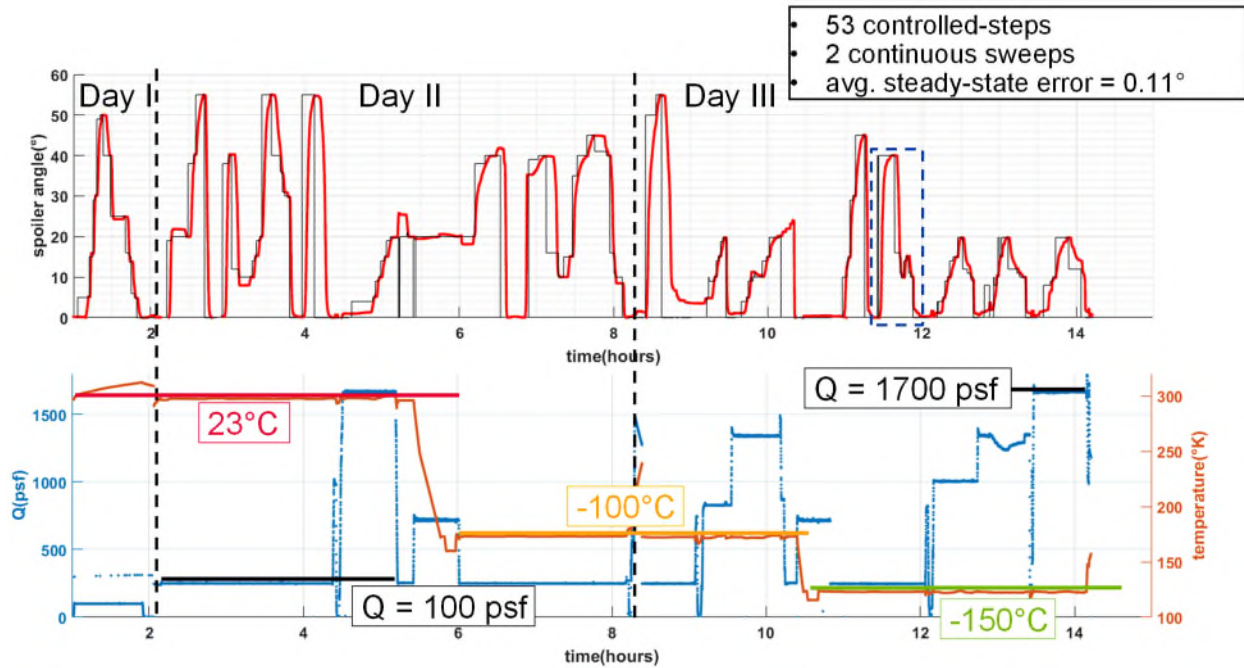


Fig. 10 Continuous (no access) testing of the 2D RCA spoiler in a cryogenic WT test environment

Two other tests were conducted with the 2D RCA Spoiler system to flesh out the system capability. First, a 0.5" fence was installed to trip the flow to demonstrate the robustness of the RCA system controller to unsteady flow. Figure 11 shows the controller moving the spoiler in 5 degree increments from 0 to 20 degrees ($T=-100^{\circ}\text{C}$, $Q=250$ psf). The oscillation of the spoiler position at 20 degrees resulted from an initial overshoot and identified the need for further tuning of the control system.

Performed:
 continuous sweep from 0-20°
 5° steps from 0 to 20 to 0°
 $Q = 250$ psf
 $T = 23$ and -100°C

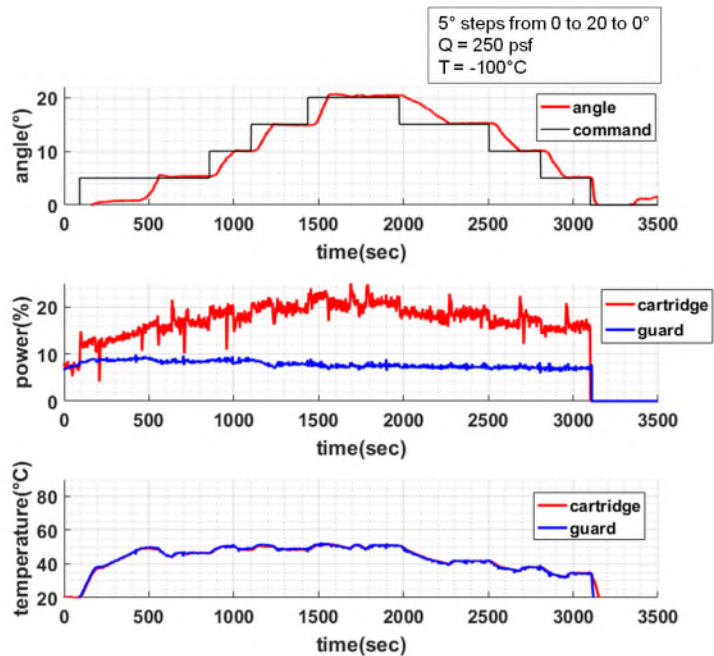
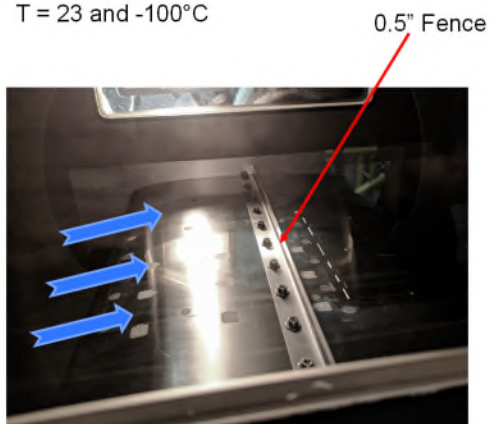


Fig. 11 Evaluation of 2D RCA Spoiler control system under forced unsteady flow conditions

For the second test, the fence was removed, and the spoiler mechanically pinned at 12 degrees with the SMA element disconnected at one end. During this test the SMA element was heated although the spoiler did not change position and pressures were monitored. This test, results shown in Figure 12, demonstrated that heating the SMA element did not influence aerodynamic measurements, thus providing confidence that the boundary layer is undisturbed with SMA activation.

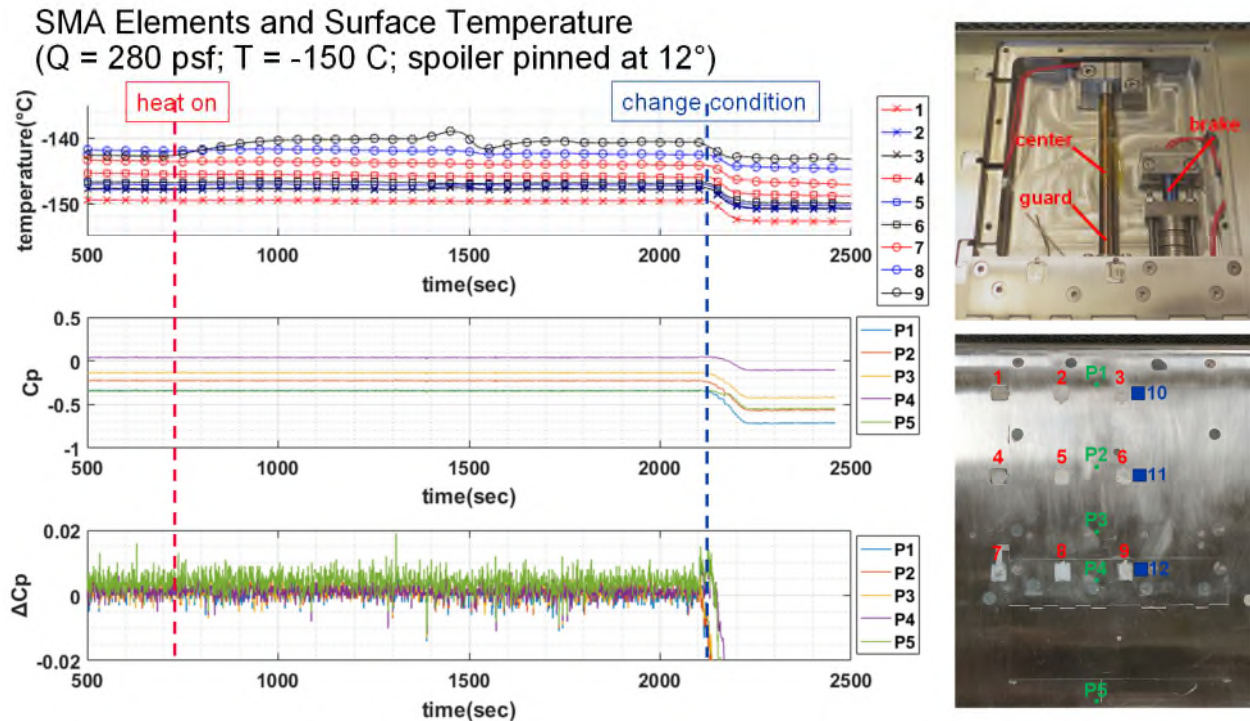


Fig. 12: Demonstration that heating the SMA elements did not influence aerodynamic measurements.

VI. Next Steps

The next step in the validation of RCA technology for cryogenic high-speed wind tunnel testing will be the testing of a modified 4.5% 787-8 half-model with multiple RCA surfaces. In preparation for this test, a 3D wing section with an RCA aileron and outboard spoiler was built and tested in the cryogenic chamber at PETW in early 2019, results to be discussed in a future report. Figure 13 shows a schematic of the 3D wing section. This test has enabled the team to refine the actuation system design, confirm instrumentation and wire routing, develop instrumentation calibration procedures, and test the control system at cryogenic temperature and with representative loads in advance of the 4.5% semi-span test in NTF and ETW. The 787-8 wing planform, and the regions of RCA operated control surfaces, is shown in Figure 14. Three primary RCA surfaces: the aileron, outboard spoiler (#7) and inboard spoiler (#1) were designed and will be tested based on lessons learned and best practices from each of the previous tests over the preceding 4+ years.

- Cutout of OB spoiler and aileron section
- Tested in two entries in cryo-chamber
- Validation of mechanical approach

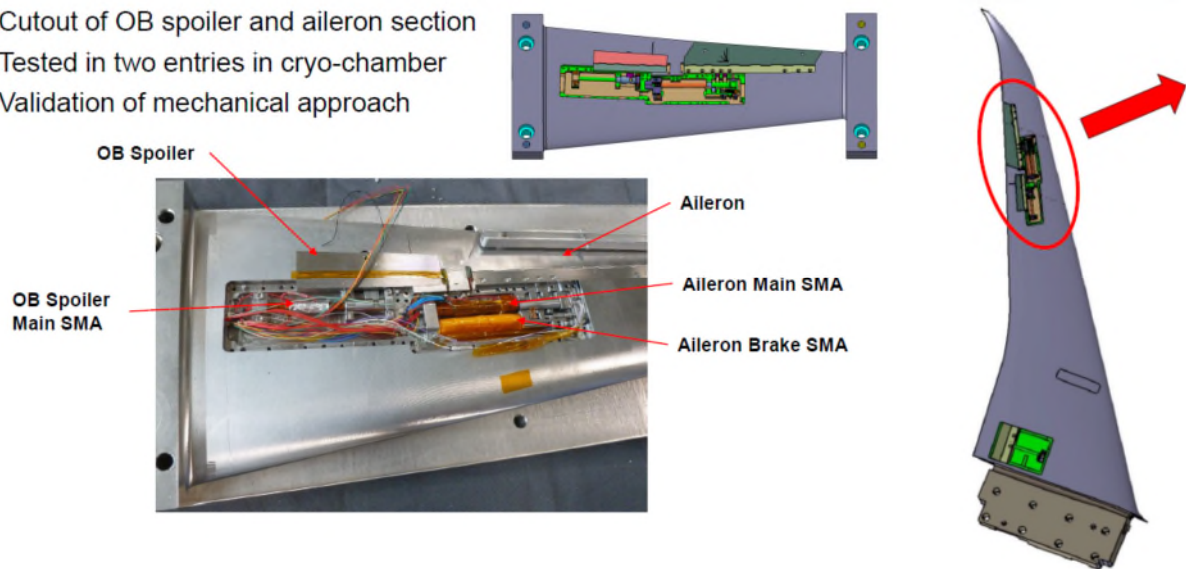


Fig. 13 3D wing section with RCA aileron and outboard spoiler

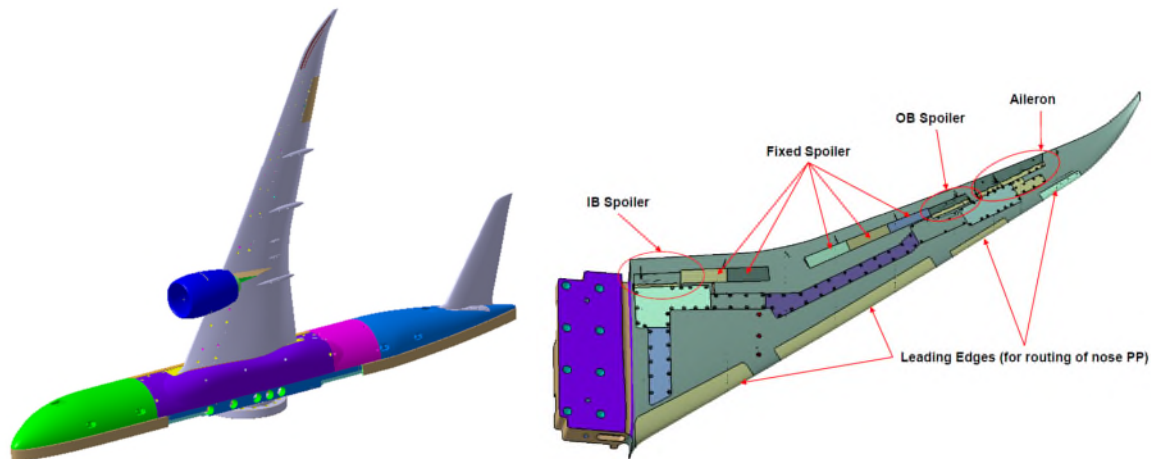


Fig. 14 Model of 787-8 half-model with multiple RCA surfaces

VII. Conclusion

The international team from Boeing, European Transonic Windtunnel, NASA Langley Research Center, and model manufacturer Deharde Maschinenbau continues to develop and test numerous SMA based RCA components in cryogenic, low and high-speed wind tunnels to validate this technology. The team is showing that RCA technology enables increased productivity, improved data quality, and reduced cost of wind tunnel testing. The RCA components, which must survive high speed (Mach 0.8+) cryogenic (-150 °C) and high loading (q up to 2800 psf) conditions, are enabled by Shape Memory Alloy (SMA) elements which provide solid state, rugged, highly integrated actuators capable of moving and controlling the model parts. The authors consider Remote Control Actuation (RCA) of wind tunnel models as the next paradigm shift in wind tunnel testing.

Acknowledgments

As with such any such large complex project spread over so many years, there are too many “thank you’s” to fit into a single paragraph. However, we can say that this project would not have been possible with the cooperation and collaboration from a large crowd of interested parties from Boeing, NASA, outstanding German suppliers & contributors such as Deharde and ETW - friends and colleagues all – and finally the U.S. and German governments.

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