Development of a Dynamically Scaled Generic Transport Model Testbed for Flight Research Experiments

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Abstract:

This paper details the design and development of the Airborne Subscale Transport Aircraft Research (AirSTAR) test-bed at NASA Langley Research Center (LaRC). The aircraft is a 5.5% dynamically scaled, remotely piloted, twin-turbine, swept wing, Generic Transport Model (GTM) which will be used to provide an experimental flight test capability for research experiments pertaining to dynamics modeling and control beyond the normal flight envelope. The unique design challenges arising from the dimensional, weight, dynamic (inertial), and actuator scaling requirements necessitated by the research community are described along with the specific telemetry and control issues associated with a remotely piloted subscale research aircraft. Development of the necessary operational infrastructure, including operational and safety procedures, test site identification, and research pilots is also discussed.

The GTM is a unique vehicle that provides significant research capacity due to its scaling, data gathering, and control characteristics. By combining data from this testbed with full-scale flight and accident data, wind tunnel data, and simulation results, NASA will advance and validate control upset prevention and recovery technologies for

transport aircraft, thereby reducing vehicle loss-of-control accidents resulting from adverse and upset conditions.

1.0 Introduction

The NASA Aviation Safety and Security Program (AvSSP) was established to develop technologies for improved safety and security of commercial transport aircraft. The Single Aircraft Accident Prevention (SAAP) Project of the AvSSP focuses on the development of technologies to reduce aircraft accidents resulting from loss of vehicle control (or upset) as well as failures. According to the National Transportation Safety Board's accident database, 40% of all commercial aviation fatalities from 1990 – 1996 were due to loss of control. Control Upset Prevention & Recovery (CUPR) technologies being developed under SAAP provide control under adverse flight conditions in order to accommodate failures, prevent loss of control, and recover control during loss-of-control events. Technologies being developed include enhanced models of vehicle dynamics to characterize upset conditions, failure detection and identification (FDI) algorithms, and adaptive guidance and control (G&C) laws. The upset dynamics models have been developed for integration into an enhanced aircraft simulation that is being created for improved upset recovery training, and to support the development and evaluation of the FDI and G&C algorithms. These algorithms are being developed for use onboard transport aircraft for improved situational awareness and control under adverse and upset conditions related to loss-of-control events. Validation of these technologies is therefore critical.

The AirSTAR testbed is being developed to provide an in-flight validation capability for high risk flight testing of these AvSSP technologies. To accomplish this, researchers at

LaRC have undertaken the task of designing, fabricating, and operating a turbine powered, dynamically scaled transport aircraft. While the challenge to design and fabricate this research vehicle was significant, a more encompassing task of building and training an infrastructure to operate the aircraft in a continuing safe and efficient manner also began to evolve. This task included the education and training of a core group of pilots, the development of safety and operational procedures and checklists, the training of essential ground support personnel, and the identification and coordination of test sites external to NASA Langley.

The rest of the paper is organized as follows: Section 2 describes the research requirements for the AirSTAR testbed (including motivation and research goals); Section 3 describes the risk mitigation effort undertaken in establishing the testbed (including the development of a pilot training program, the establishment of a phased aircraft development plan, and the development of a transport model simulation); Section 4 describes the transport model development (including dynamic scaling requirements, control and telemetry requirements, the model aircraft design, fabrication, and testing); Section 5 describes support activities in the development (including safety procedures and test site identification); and Section 6 provides some concluding remarks. The development of ground facilities for this testbed will be presented in a subsequent paper.

2.0 Research Requirements

2.1 *Motivation*

An integrated validation process is being developed under SAAP in parallel to the technology development to provide advanced methods for analysis, simulation, and experimental testing under adverse and upset conditions. Experimental testing will involve both ground and in-flight testing. In-flight testing under adverse and upset conditions poses a special challenge due to the high risk of the required flight maneuvers. Figure 1 shows a depiction of a loss-of-control accident as it relates to angles of attack and sideslip angle. High-risk operation at extreme flight conditions outside of normal operation precludes the use of full-scale manned aircraft testing. The AirSTAR subscale flight test capability is therefore being developed to address these high-risk conditions.

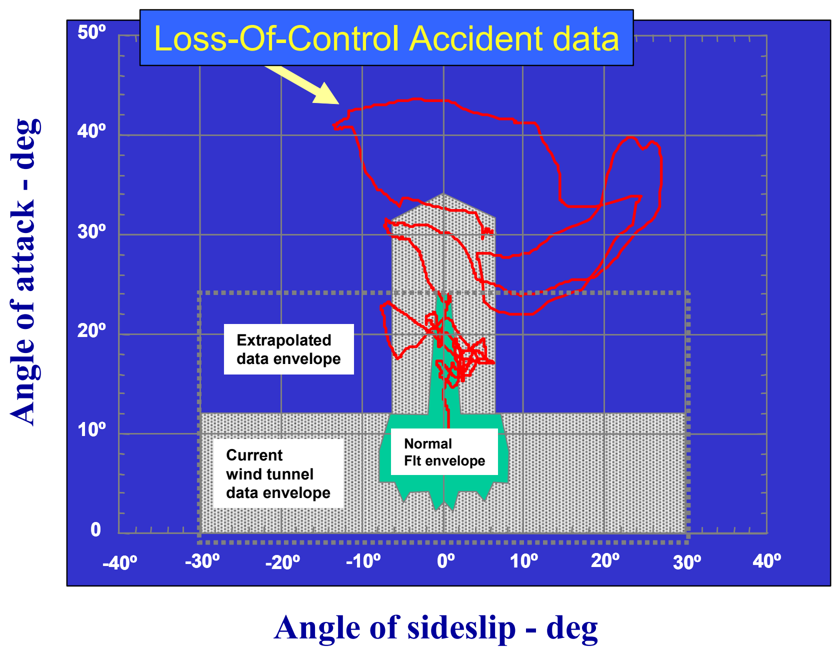

Figure 1. Plot showing a transport loss-of-control accident relative to angle-of-attack and sideslip

2.2 *Research Goals*

The goal of the AirSTAR testbed is to provide an in-flight research environment for the evaluation and validation of safety-critical technologies, including the flight validation of: vehicle dynamics modeling and simulation technologies for upset characterization, failure detection and accommodation system technologies, and upset recovery system technologies.

3.0 Risk Mitigation

3.1 *Pilot Training Program*

After examining the risk associated with flying a subscale research vehicle, it became obvious that pilot proficiency plays a major role in the successful operation of the vehicle. According to a survey conducted by the Jet Pilots Organization (1) at model jet events during 2003, over 50% of the known causes of turbine vehicle crashes were due to pilot error. In order to assure a long life and to be able to operate the research vehicle in various upset conditions, a capable and practiced group of subscale turbine pilots is required. To this end, a pilot training program was developed to grow the necessary skills. This program has two main thrusts, one being the field operation of increasingly more complex subscale air vehicles, and the other being the development and use of a GTM simulator.

3.2 *Phased Model Aircraft Approach*

An array of airplanes was utilized in the pilot training program as shown in Figure 2. Phases 1 and 2 of the program make extensive use of commercial-off-the-shelf (COTS) aircraft in an effort to control cost and maximize flight time. In order to assess the initial skill level of the Langley pilots, the training program started off with a propeller driven, aerodynamically stable model. Training then progressed in Phase 1 to faster and more agile propeller and ducted fan powered aircraft.

Phase 2 of the program began with the introduction of turbine powered aircraft. As a guideline for the turbine portion of the training program, the rules and regulations of the

Academy of Model Aeronautics (AMA) turbine waiver process were followed. Although Langley's turbine flights do not occur at AMA sanctioned fields (therefore the AMA guidelines do not apply), the guidance provided by the AMA was very beneficial in developing this portion of the program. NASA Langley currently has four pilots who have qualified for the AMA turbine waiver. The turbine aircraft employed in this phase of the program are all COTS models, with some slight modifications. These planes enable the Langley pilots to amass critical flight time on a turbine aircraft, while doing so with affordable, robust, and proven airframes. The KingCat, T-33, and L1011 are the workhorses of the Langley turbine training vehicles.

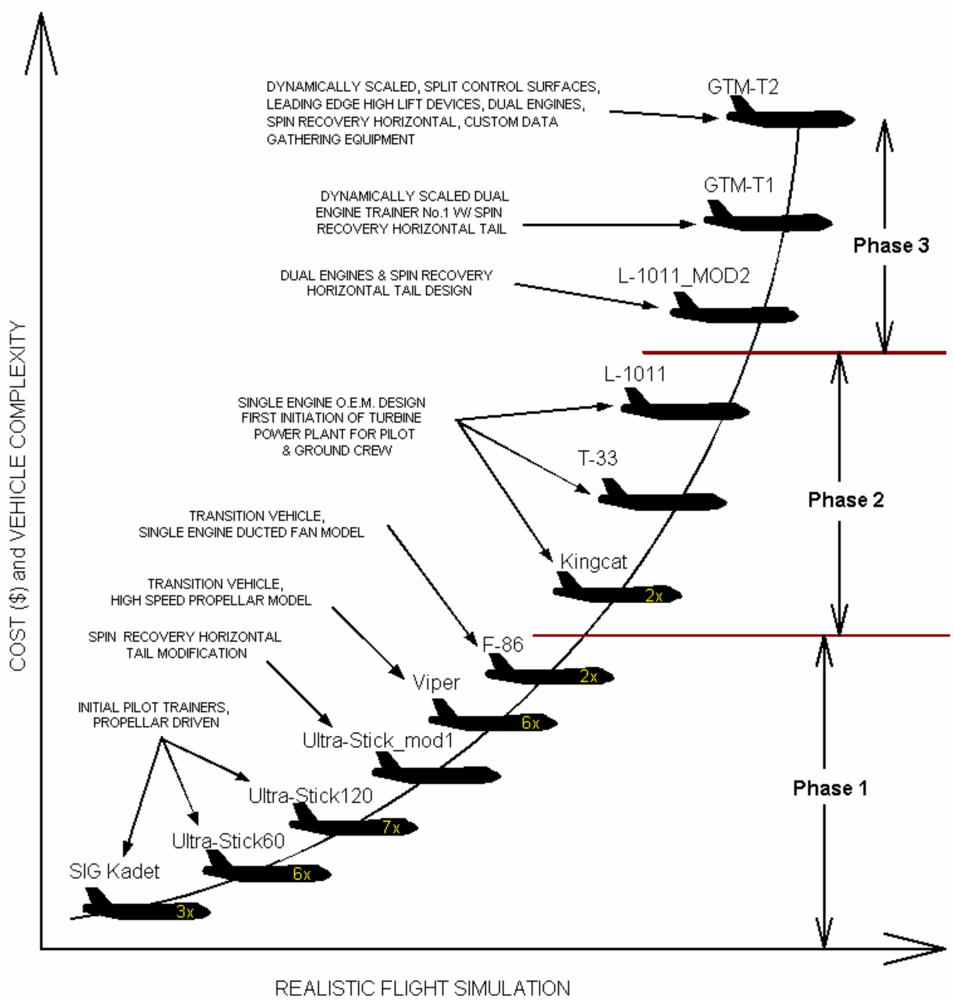

Figure 2. Airplanes utilized in pilot training program

Phase 3 of the training program is comprised of twin turbine, swept wing, transport aircraft which have been either highly modified or entirely designed and fabricated by Langley personnel. The L1011 Mod2 aircraft was modified in-house for dual turbine and spin recovery operation. The T1 and T2 aircraft were designed and fabricated in-house as dynamically scaled 5.5% models of a twin-engine transport aircraft. The T1 serves primarily as a trainer, but also is used for various subsystem checkout and validation. With the T2 airplane, the main research aircraft, weight has been taken out of the airframe through the use of advanced composite materials in place of fiberglass, which allows for a greater payload of research instrumentation.

3.3 *GTM Simulator*

As another component of the risk mitigation scheme, a real-time piloted simulation of the GTM was developed to support pilot training and to provide a tool for evaluating the handling characteristics of the flight vehicle. The simulation was based on a non-linear, six degree-of-freedom model that included aerodynamic, thrust, control system, geometry, and mass properties. The aerodynamic model was based on an extensive series of wind tunnel tests conducted at NASA LaRC, using a model with moldlines identical to the GTM. During these tests, over 46,000 data points were obtained to model the effects of angle of attack, angle of sideslip, control deflections, angular rates, and component effects. These data points were used to develop a non-linear mathematical representation of the aerodynamic properties for angles of attack ranging from –10 to +80 degrees and angles of sideslip from –45 to +45 degrees. The dynamic model was hosted on a desktop PC and was interfaced with a typical RC pilot control box utilizing a high-resolution visual display.

An important benefit of the simulator is that it provides a tool for the pilots to learn the basic handling qualities of the model as well as practice flight procedures during degraded performance conditions. For example, the simulator allows the pilots to practice recovery from engine failure during critical flight conditions such as takeoff or landing. In addition, the simulator is invaluable for flight planning by providing estimates of structural loads during test maneuvers.

4.0 Model Development – GTM T2

4.1 *Dynamic Scaling Requirements*

In order for the model to appropriately represent the flight characteristics of a full scale airplane, specific dynamic scaling requirements are imposed on the subscale aircraft. Among these are dimensional, weight, inertial, and actuator response scaling issues. Table 1 lists some of the full scale aircraft properties and the requisite model properties.

Table 1 – Selected scaled parameters of a 5.5% model

	Length	Wingspan	Weight	Roll inertia	Airspeed	Altitude
Full Scale Transport	145.5 ft	124 ft	200,000 lbs	2.64e^6 sl-ft^2	320 mph	13000 ft
5.5% Model	96 in	82 in	49.6 lbs	1.33 sl-ft^2	75 mph	1000 ft

In general, assuming a scale factor of K, then dimensional scaling is proportional to K^1, area scaling to K^2, weight and volume scaling to K^3, mass moments of inertias to K^5 and response to $\sqrt{K}$. For example:

$$\begin{aligned}\text{Model wingspan} &= \text{Full scale wingspan} \; * \; K^1 \\ &= 145.5 \text{ ft} * 0.055^1 \\ &= 8 \text{ ft}\end{aligned}$$

What this means to the model designer is that while size and weight go down for a subscale design, response time (such as for actuation systems) gets faster.

An added complexity to the general scaling requirements described above is that because the model will be flying at a different altitude than the full scale aircraft, the density of the air must be taken into account. This ratio of air densities affects the model target weight as follows:

$$\text{Model weight} = \frac{\text{Airplane weight} * K^3}{\dfrac{\text{Airplane air density}}{\text{Model air density}}}$$

It can be seen from Figure 3 that model weight (assuming flight at sea level) is determined from aircraft weight/altitude, or conversely, a given model weight can represent different combinations of aircraft weight/altitude. A more in-depth discussion

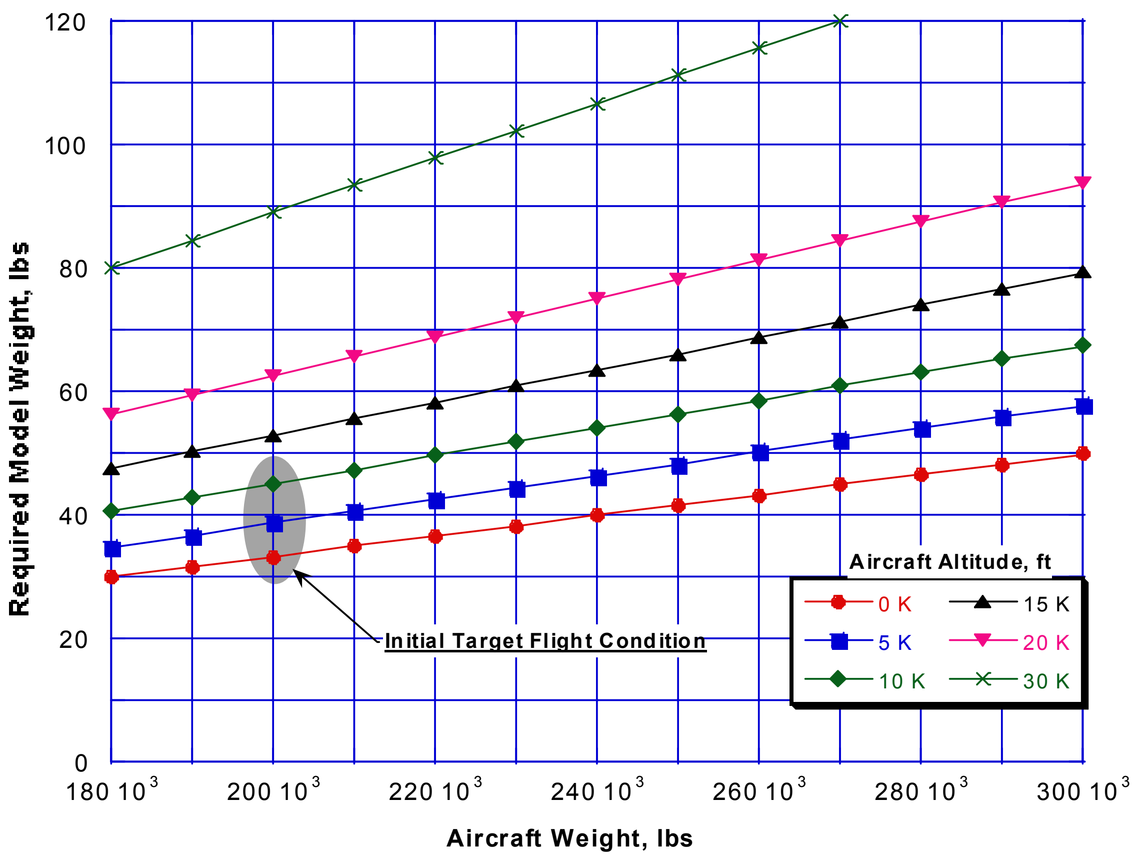

Figure 3. Model weight as a function of full scale weight and altitude

of similitude and scaling requirements can be found in NASA publications by Gainer and Hoffman (2) and Wolowicz et al. (3).

An initial scaling factor of 5.5% was chosen based on the fact that Langley had previously fabricated and extensively tested in it’s wind tunnels a model of that scale. The aerodynamic data from those wind tunnel tests would be used to develop the simulator described above. Also, the original fabrication molds were still in existence which provided a time and cost savings in fabrication of the model. A feasibility study was conducted to determine if the dynamic scaling requirements of a 5.5% model could be met given the control, data, operational, and telemetry requirements. The results of the study showed that the research instrumentation and 5.5% dynamic scaling requirements could co-exist in an aircraft of that size. Other requirements such as rigidity, symmetry, flight time, CG location, take-off and landing speeds, propulsion, video, and control surface deflection were addressed in the design.

4.2 *Control and Telemetry Requirements*

The unique research requirements of the AirSTAR testbed dictate several challenging control and telemetry solutions. Specific downlink data requirements include the following: potentiometers at all control surface hinge points for precise position feedback; GPS, attitude, heading, airspeed and acceleration data for aircraft positions and rates; video from an onboard camera; and various status parameters such as commanded control surface position, throttle position, and battery voltage. In total there are over 60 channels of data that are transmitted from the airplane at rates ranging from 27 Hz up to 216 Hz. Once this data stream is received in the ground station, a real-time control system merges these inputs with the inputs from a research pilot and, using the researcher supplied control algorithms, computes new control surface commands to send to the airplane. L-band and S-band transmitters and receivers are utilized for these links. This closed loop control system must operate reliably at 200 Hz. Operational requirements dictate that the test volume of the aircraft should be approximately 2 miles x 1 mile and 1 mile high. Details of the development of the ground station and its capabilities will be presented in a forthcoming paper.

An additional telemetry uplink to the aircraft is used for the safety pilot, who utilizes a COTS R/C transmitter and receiver operating at 72 MHz. A remotely actuated switch directed by the safety pilot dictates whether control of the airplane comes from the research pilot or the safety pilot.

4.3 *Design*

Since the size, weight, and inertias of the vehicle are all dictated in the research requirements, the challenge is to design the airframe and all of its associated substructure and assemblies to meet the target values. The vehicle design starts with the creation of Pro-Engineer Solid Model parts that represent the conceptual vehicle with its individual parts and components. All of the vehicle’s components are modeled as accurately as possible with regard to size and weight. Commercial-off-the-shelf parts are measured, weighed, and then replicated using the Pro-Engineer Solid Model software. Sub-assemblies are then created from these individual parts to represent the landing gear, fuselage, and wing assemblies, the pneumatic system, etc. A final assembly, shown in Figure 4, is then created from combining all of the sub-assemblies. From this final assembly, weights and inertias can be estimated.

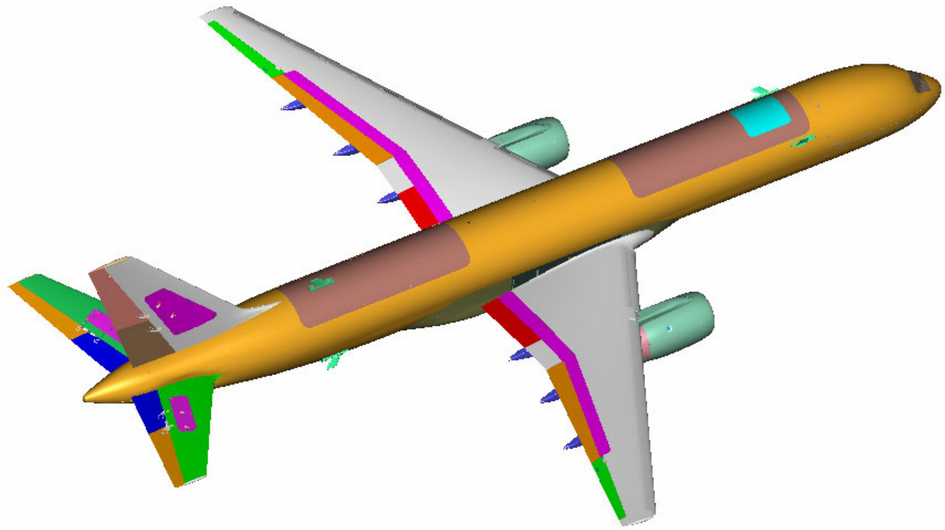

Figure 4. The GTM-T2 Pro-Engineer solid model (6th Generation)

4.4 *Fabrication*

A fiberglass and honeycomb sandwich composite is used to form the fuselage. The wings and empennage are fabricated from carbon and balsa sandwich construction to make possible a high load carrying capability and light weight. Aircraft plywood is used throughout fabrication for ribs, bulkheads, and spars. Aluminum is used sparingly in such places as the wing/pylon mount, the spin recovery system, and landing gear components.

Figure 5. The starboard fuselage skin with ribs & sub-structure located and bonded

4.5 *Testing*

The ground testing for the vehicle consists of three phases: the aerodynamic load testing, the inertial testing, and the taxi testing. The aerodynamic load testing is done with lead shot bags distributed in an elliptical shape over the wings. The inertial testing is done in the pitch, yaw, and roll orientations using a bi-filar pendulum. Inertial testing of the T1 aircraft yielded results which were within 2% of the estimated Pro-Engineer values. The taxi testing (low and high speed) is used to establish ground handling and braking characteristics and for overall system checkout before the first flight.

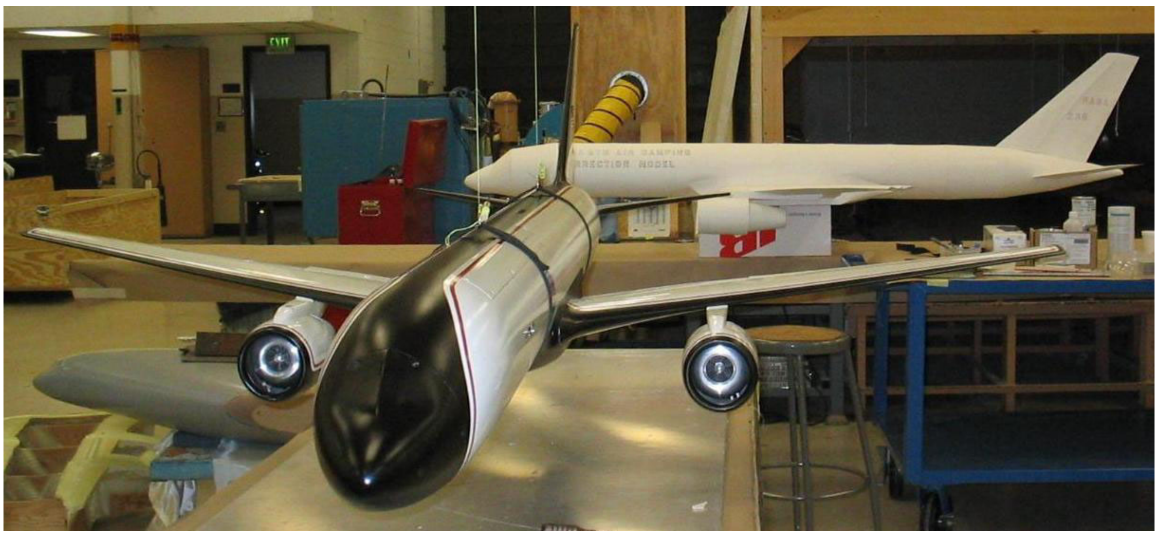

Figure 6. Foreground: the 5.5% GTM undergoing "yaw" inertial testing on a bi-filar pendulum. Background: the 5.5% GTM air damping corrections model (paper construction)

5.0 Support Development

5.1 *Safety procedures*

Safety has always occupied a position of great importance in NASA research and development programs. One of the early goals of the AirSTAR program was to determine all hazards and associated risks involved with this project. While the flying of Remotely Piloted Vehicles (RPV) is not new, intentionally placing a dynamically scaled aircraft in conditions known to have caused the full scale aircraft to crash, for the purpose of trying to recover from this condition, is new and exciting research. A formal analysis was completed to identify potential hazards and their consequences and to develop the proper response. Mitigation of risk to minimal levels and the development and practice of proper responses when things go wrong are fundamental to the AirSTAR safety program. The safety of the public and NASA personnel always takes precedence over testing and research.

Checklists, inspection lists, logbooks, and procedures covering all areas of operation were created to expose and prevent many potential problems. Some examples of these 21 documents are pre-flight inspection, post-flight inspection, battery charging, flying site inspection, starting procedures, emergency procedures, and maintenance.

The pilot training program, as discussed earlier, plays a large role in the development of overall project safety. Not only does it mature pilot skills to the appropriate level, but it also helps develop safe handling and operating procedures for the AirSTAR team. The training program is where checklists and procedures are field tested on standard aircraft with less potential risk.

Individual components were tested and analyzed in an effort to reduce the consequences of failure. Electronic components were evaluated in such areas as loss of signal, loss of power, and loss of electrical ground to develop failure modes and responses. Efforts have been made to eliminate single point failures that would result in the loss of the vehicle. Appropriate flight termination mechanisms and procedures were incorporated for emergencies, to minimize potential damage to the environment, surroundings, and personnel.

5.2 *Test site identification*

When considering a potential test site for the AirStar testbed, two main factors are considered: does the site maximize the likelihood of a successful flight; and does the site provide adequate isolation so that if there is an incident, damage to surrounding personnel and property is minimized? Since the AirSTAR is a testbed with plans to operate on a frequent basis, travel and the associated cost for the operations are also taken into consideration. Most of the turbine training flights have taken place at Aberdeen Field in Smithfield, VA. This is a private airfield with a 60' x 6000' runway. It is located within 45 minutes of NASA LaRC and is utilized two to three times per week by the pilots. The field provides a very good environment for training flights of the low risk turbine models.

However, because of the increased operations area and the nature of the research maneuvers and the associated risk, flights of the T2 airplane require a larger and more isolated test area. For this reason, research flights of the T2 will most likely take place at a controlled access government facility. To date, the project has identified Wallops Flight Facility on the Eastern Shore of VA as a potential test area.

6.0 Conclusions

The NASA Langley AirSTAR testbed consists of a unique ground station and remotely piloted aircraft which will be utilized to conduct flight research experiments related to control upset prevention and recovery of air transport vehicles. Integrating this data with data from wind tunnels and full scale flight experiments will enable the creation of more realistic flight simulators for pilot training and the development of safer and more robust transport aircraft of the future, all with the goal of reducing loss of control aircraft accidents.

Acknowledgment

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