THE APPROACH AND LANDING TEST PROGRAM OF THE SPACE SHUTTLE ORBITER 101

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Abstract

The Space Shuttle is the National Aeronautics and Space Administration (NASA) response to the requirement for a reusable space booster. It is comprised of a manned Orbiter booster, an external tank (ET), and two solid rocket boosters (SRB), all joined together by linking attack struts to provide a launch vehicle capable of lifting a 65,000 pound payload into Earth orbit.

The first staging during launch occurs when the SRB's are separated. The SRB's are parachuted back to be recovered from an ocean landing and reused. The Orbiter and ET continue until the ET fuel is exhausted, and it too is jettisoned to be destroyed upon reentry. The Orbiter then finalizes its orbit requirements with the Orbital Maneuvering System (OMS). Deorbit is initiated by the OMS, and the Orbiter enters the Earth's atmosphere and decelerates to subsonic speed. The Orbiter then glides to a landing at the selected landing site.

The Approach and Landing Test was conducted to verify the landing capability of the Orbiter. The preliminary mated test phases led up to the free flight tests and were used to check out software and hardware systems in a constrained environment. The tests were conducted with the Orbiter mounted atop a modified 747 commercial airliner, and verified the systems required for separation. The first free flight of the Orbiter occurred on August 12, 1977 and was manned by astronauts Fred Haise and Gordon Fullerton. Free flight two occurred on September 13, 1977, with astronauts Joe Engle and Richard Truly flying the Orbiter. Three other flights were eventually flown with the two crews alternating flights.

The preparations for the flight, the engineering problems and considerations which arose before and during the flights, and the unique approach to the flight testing are discussed in this paper. Some comparisons of predicted and flight results are presented, and excerpts from the pilot reports highlight the paper.

Shuttle Flight Test Overview

Flight testing of the Shuttle is comprised of two programs. The Approach and Landing Test (ALT) program was conducted in late 1976 through November 1977 to investigate the low speed characteristics of the Orbiter alone. The Orbital Flight Test (OFT) program is to commence in late 1979 and will be conducted to test the complete flight regime of the Shuttle configuration.

This paper covers the testing accomplished during the Approach and Landing Test. The innovative aspects of the Orbiter, the ALT program, and the testing methodology will be examined. Highlights of the test flights will be noted and some comparisons of flight and predicted data will be shown.

Shuttle Transportation System Concept

The Shuttle Transportation System (STS) represents the achievement of the national goal to create a reusable booster to shuttle to and from earth orbit. The STS has four major components; the Orbiter, which houses the crew and payload, an external tank which carries the fuel for the three Orbiter engines, and two solid rocket boosters (SRB's) to provide the necessary additional thrust. The Orbiter and SRB's are designed to be recovered and reused many times; the external tank is the only component which is not recoverable.

A typical operational mission will see the Shuttle launched vertically. Approximately two minutes into the flight the SRB's will have exhausted their fuel and will be jettisoned. The Orbiter and external tank will continue until the fuel in the external tank is exhausted, and the tank is then separated from the Orbiter. The final burn to achieve the desired orbit is then accomplished with the Orbital Maneuvering System (OMS) engines which have self-contained fuel systems. With the attainment of the correct orbit, the Orbiter is positioned in the proper attitude for payload deployment, operations or retrieval as required for the particular mission. The completion of the orbital mission signals the deorbit preparations. Deorbit is attained by retrofire of either the OMS or the Reaction Control System (RCS), after which the Orbiter goes through a period of free-fall, and is positioned in the proper reentry attitude. The entry interface is attained at 400,000 feet; and from there, the Orbiter gradually transitions from spacecraft controls to atmospheric controls using the aerodynamic control surfaces. The Orbiter decelerates from Mach 25 to subsonic speeds in approximately 20 minutes, and enters the approach and landing flight regime. The Orbiter then continues its unpowered descent to a conventional runway landing at a designated site.

The Shuttle concept utilizes digital computers to automatically guide, stabilize and control the vehicle through all flight phases. The launching of four linked bodies, the orbiting and reentry of a winged body, heat absorption by non-oblative shields, unpowered reentry and approach, and automatic approach to landings are to be characteristic events of the Shuttle era. Even as Kelly Johnson evolved the revolutionary design of the P-38 to satisfy range, climb and maneuver requirements, so the Shuttle utilizes departure from past methods and techniques to attain its goal. Attention to schedule allowed the "skunk works" to turn out the first single-engine operational jet fighter, the P-80, in only 143 days. The Shuttle is also bound by severe schedule constraints, mandated by international commitments to payload customers. Innovative testing, analyses and integrative efforts are required to maintain the complex time table. The high-flying U-2 and the spectacular SR-71 are manifestations of the technological advancements generated by the "skunk works." The flight regimes through which the Orbiter must pass impose even more severe conditions to the Orbiter requiring many technological innovations. Only the X-15 has been able to approach the regime of the Orbiter, and to provide data and insight into potential problem areas. The Orbiter then should be expected to have unusual design characteristics, as it in fact does.

Orbiter Description

The Orbiter is unique in that it is designed to perform the functions of a spacecraft, and also those functions associated with conventional aircraft. As a spacecraft, it must be able to sustain the crew and systems in space, maneuver in space, deploy and retrieve payloads and perform deorbit targeting and engine firing. As the Orbiter enters the atmosphere, transition to its role as an aircraft occurs. Conventional stability and control, aerodynamic and aeroelastic concerns become prevalent as the Orbiter decelerates from hypersonic regimes to the Approach and Landing Test regime.

The aerodynamic performance of the Orbiter is also unique in that the longitudinal center of gravity travel is not restricted to maintain positive static margin. Design of the Orbiter allows for a negative static margin of two percent of body length, which equates to approximately 5.5 percent of the mean aerodynamic chord. Stability is artificially maintained by the flight control system from the maximum Mach number of roughly 30, down to the touchdown speed of 185 knots. The Orbiter can be trimmed to fly hypersonic lift-to-drag ratios of 1.3 during entry phase, and 4.9 at subsonic speeds with the speedbrake closed. Nominal approach during the Terminal Area Energy Management (TAEM) phase is along a 22-degree glide path angle, with a short-final approach along a 1 1/2 degree glide path.

The Orbiter vehicle itself is comparable in size to a DC-9, having a length of 122 feet and a wing span of 78 feet. The Orbiter dry weight is about 150,000 pounds and it can deliver payloads weighing up to 65,000 pounds with lengths up to 60 feet and diameters of 15 feet.

The Orbiter wing is essentially of double delta geometry with the forward leading edge sweep of 81 degrees, and the basic trapezoidal wing leading edge of 45 degrees. This double delta wing shape was chosen to provide high lift efficiency and a good cross range capability. Airfoil design is based on a standard NACA shape with camber distribution which becomes negative at the trailing edge of the wing to optimize total wing loads.

Major aerodynamic surfaces that control the vehicle during entry phase are the four elevons, speedbrake panels, which also act as rudder, and body flap. The elevon panels, located two on each wing, act as both pitch and roll control devices. Movement of all four panels in the same direction constitute pitch control. Two panels moving differentially with respect to the centerline control the roll axis as ailerons. The aileron is also used as the yaw damping device from the atmospheric entry point down to Mach 4.5 due to the ineffectiveness of the rudder surface in these regimes. At Mach 4.5 the rudder surface is activated and gradually takes over the yaw control as the aileron takes over conventional roll control at the lower supersonic flight regimes. The rudder/speedbrake consists of two wedge airfoil panels, which, when deflected in opposing directions, form a speedbrake used for drag and pitch modulation from entry through landing. The body flap is a pitch trim surface which is used to null the elevon deflection about a nominal trim point. As such, the body flap operates on a hysteresis cycle and moves only when the elevon deflection away from nominal exceeds a deadband value.

During entry phase, vehicle control is provided by the Reaction Control System (RCS) along with the aerodynamic control surfaces. These RCS jets are available in all three axes and assume control until the aerosurfaces gain adequate effectiveness with dynamic pressure. Pitch and roll RCS jets are automatically turned off when dynamic pressures exceed 20 and 10 PSF, respectively; however, the yaw RCS jets are not turned off until Mach number one is reached.

Orbiter has two independent digital fly-by-wire flight control systems, normally referred to as the primary (PFCS) and backup (BFCS), respectively. In terms of functions, the PFCS provides autoguidance flying capability (AUTO), or manual flying with stability augmentation, called Controlled Stick Steering (CSS). Nominally, the PFCS is implemented by one of four redundant synchronous General Purpose Computers (GPC's), any one of which can take over vehicle control is case the computer designated as the primary GPC fails. There is also a fifth GPC that processes data independently of the four primary GPC's and thus serves as a check on the PFCS. This computer is the heart of the BFCS. If for some reason the PFCS becomes unusable, the crew can manually switch to the backup flight system.

Navigation is maintained by inertial measurement units complemented by ground or crew updates. Onboard guidance functions control the trajectory and provide steering and thrusting commands to flight control. The flight control software then operates in a closed loop mode utilizing angle-of-attack, normal acceleration and body rate feedback signals to provide stability and initiate maneuvers. The entire Orbital mission from launch through orbit, deorbit, entry, approach and landing through rollout can be performed in the automatic mode, with the crew providing braking commands during rollout.

Manual control may be initiated at any time by several means. Either crewman may control the vehicle by manipulating a rotational hand controller (RHC), body flap, speedbrake, and rudder pedals. The RHC provides rate commands into the flight control system which computes surface deflections, rate coordination and error signals from feedback sensors before commands are passed to the surfaces. If the RHC and rudders are left in the neutral position, the vehicle software maintains the existing attitude until further rate commands are issued.

The backup flight control system does similar functions, but the crew must provide manual control of the vehicle. Navigation and guidance commands are computed and displayed to the crew so that trajectory and targeting functions may be maintained.

THE APPROACH AND LANDING TEST (ALT)

The ALT was a first step toward operational missions for the Shuttle. The prime objective of the ALT was to verify the systems design and integrated operation of the Orbiter, and to demonstrate the capability of the Orbiter to safely land at a designated runway.

Preliminary approaches to ALT were imaginative. Retractable jet engines in early Orbiter designs provided the capability of powered flight for which a flight test program would have been more conventional. The deletion of jet engines from the design made a glider of Orbiter during entry regimes, and thus a requirement evolved to hoist the Orbiter to sufficient altitude for flight testing. Several carrier aircraft were evaluated including a gigantic twin-boom design which would have straddled the Orbiter, carried it aloft and dropped it from the underside in a conventional "drop program." The concept finally adopted was to mount the Orbiter atop a carrier aircraft, two types of which were available (C5A and 747). The 747 aircraft was selected, and modifications to the aircraft initiated to make it into a shuttle carrier. Attach struts and reinforcing structure were added to the 747, as were tip fins on the horizontal stabilizers to provide additional lateral stability margins. The modified 747 and the onboard systems to provide Orbiter launch capability then became the Shuttle Carrier Aircraft (SCA).

The delivery of the SCA to Dryden Flight Research Center (DFRC) coincided closely with the delivery of the Orbiter by overland transport. Requirements to verify the mated vehicle aerodynamics prompted a captive-inert test phase with the Orbiter mounted on the SCA, but with all Orbiter systems powered down, controls locked, and no crew onboard. This test phase verified the aerodynamics, altitude capability, and launch profile of the mated configuration with tailcone. The tailcone had been added to the Orbiter aft end to reduce the anticipated buffet on the SCA empennage due to the separated flow field in the Orbiter base region. The tailcone design succeeded in reducing buffet levels and also drag, enabling the mated configuration to attain higher altitudes.

Completion of the inert Orbiter/SCA testing paved the way for captive active tests in which the Orbiter crew powered up the Orbiter systems and performed systems evaluations while in mated flight. The captive active program was divided into three flights, the first occurring June 18, 1977, and the last on July 26, 1977. The first flight was used to clear the mated vehicle for higher speeds by making surface inputs at 180 knots equivalent airspeed. Pulses were initiated from both the Orbiter and the SCA. The Orbiter speedbrakes were also opened to 100 percent deployment at the same airspeed.

The second flight extended the operational envelope of the active pair to 270 knots equivalent airspeed by performing flutter and speedbrake checks at 230 knots first, and then at 270 knots. A practice separation profile was accomplished and a checkout of the autoland feature of the Orbiter was performed.

The third flight verified the Orbiter navigation update capability, and the Orbiter trim elevator setting for launch from the SCA. The landing gear was also deployed in a test of that system.

The approach to the free-flight portion of ALT marked the time of "getting down to business" on ALT. Initial free flights were conceived with the tailcone retained to provide longer flight times and less severe approaches. Early designs allowed the tailcone to be jettisoned after the Orbiter had separated from the SCA, but this capability was eventually discarded in favor of tailcone-on and tailcone-off mated flights through separation. Consequently, three flights were conducted with the tailcone on, and two flights were flown to determine the tailcone-off characteristics.

Many flight test requirements were slated to be satisfied and only five flights were scheduled in which to satisfy the requirements. Those requirements which restrained other flights were awarded higher priorities than non-restraining requirements, and were the primary considerations in establishing the free-flight profile shapes. Initial profiles called for straight-in approaches to minimize unnecessary maneuvers on early flights. However, experience gained from lifting body flights pointed to the 180-degree approach as being superior due to the release point being closer to the landing site. Pilots felt that the 180-degree technique was desirable to feel out the aircraft prior to landing, and this approach was in fact a smaller risk. Therefore, all tailcone-on free flights were laid out utilizing 180-degree approaches; tailcone-off flight retained the straight-in approaches due to the short flight duration.

Free-flight profiles were preliminarily developed on a desk-top computer and perfected in engineering or integrated simulations. Profiles were tailored to provide the maximum amount of test data in conjunction with the maneuvers required. Crew inputs were evaluated with simulated systems failures or malfunctions. Timing was especially critical and events were modified frequently until the optimized profile was attained.

A short highlight of each flight is presented next. Excerpts from the crew comments are included to provide a scenario of the cockpit view.

Free-Flight One Highlights. The first free flight of the Orbiter occurred on August 12, 1977. The flight profile had been defined utilizing lifting body experience in that the only maneuvers planned were a practice landing flare at altitude and a 180-degree turn to final approach. The separation and avoidance maneuvers were nominal with the exception of a General Purpose Computer (GPC) failure at separation, which had no effect on the vehicle performance. The flight proceeded according to the nominal profile, and the following excerpts taken from the crew reports are presented to summarize the flight:

° "Practice flare leveled at 20,000 feet; roll control from roll inputs during the deceleration was more sensitive than experienced in the Shuttle training aircraft. Pitch control was very precise which allowed very small inputs to be made as the airspeed decreased. There were no apparent handling characteristic changes with decreasing airspeed. Attitude control of both roll and pitch was very tight whenever the rotational hand controller was in detent. There were no visible overshoots in either the pitch or roll axis after making an attitude change and no Dutch roll oscillations were noted."

° "No trim change was apparent with speedbrake deployment. They were retracted passing 2000 feet above ground level, again with no apparent trim change."

° "During base and final turns airspeed was easily controlled to within one knot of desired."

° "Landing preflare was initiated at 900 feet AGL, and touchdown was felt as the vehicle passed through 185 knots."

Free-Flight Two Highlights. Free-flight two was planned to evaluate Orbiter controllability up to 1.8 g's, and the effects of software and crew-initiated surface inputs to the vehicle. High speed inputs were made at 294 knots. The 1.8 g turn was initiated at 300 knots as the Orbiter banked through 45 degrees, and was maintained through a heading change of 135 degrees. Low speed test inputs were then initiated at 195 knots as the pilot took control of the vehicle. After the turn to final approach at 270 knots, the speedbrake was deployed and surface inputs again initiated. The commander resumed control of the vehicle at 2000 feet AGL, and the Orbiter touched down 682 feet past the planned point. Crew comments on the flight emphasized the following:

° "Load factor was easily controlled throughout the decelerating turn."

° "Response and damping of the surface inputs was solid, even for the 195 knot test cases."

Free-Flight Three Highlights. The third free flight was the last flight with the Orbiter tailcone, and was designed to examine the effects of center-of-gravity shifts and to evaluate the closed-loop AUTOMATIC control mode. The planned profile was identical to that of free-flight two, with the Orbiter center-of-gravity moved aft two percent of body length (which equates to approximately 5.5 percent of the mean aerodynamic chord). According to plan the AUTOMATIC flight control mode was initiated during the final approach and the vehicle interaction with the Microwave Scanning Beam Landing System (MSBLS) was also verified. "As the roll/yaw AUTOMATIC pushbutton was depressed, a sharp roll input and corresponding lateral lurch was observed." This was due to a ten percent deviation in the roll steering pointer deviation. The lurch caused the RHC to be deflected and downmoded the vehicle. The needles were then centered and AUTOMATIC mode was selected in both pitch and roll/yaw axes. The AUTOMATIC mode "was very smooth with the vehicle tracking precisely down the glideslope and centerline. Airspeed increased very slowly to 270 knots. Automatic guidance had begun to deploy the speedbrakes, which had reached 30 percent when manual control was resumed." Landing approach and touchdown were nominal, but braking caused severe vibrations which required some brake tuning prior to the next flight.

Free-Flight Four Highlights. The removal of the Orbiter tailcone for free-flight four was momentous in that the SCA estimated altitude limit was reduced by 4000 feet, effects of the separated flow off the Orbiter aft end were uncertain, and the free-flight characteristics of the Orbiter were significantly different. Consequently, the mated portion of the flight was dedicated to buffet measurements over the SCA and the Orbiter, flight control systems checks and a practice separation profile. A yaw damper onboard the SCA was evaluated as a potential means of reducing buffet levels, but had negligible effects. The mated checks were performed satisfactorily, and the separation of the Orbiter in the entry configuration was effected at an altitude of 20,200 feet AGL. The first free flight of the Orbiter in the tailcone-off configuration lasted for two minutes and 35 seconds, less than half the duration of the tailcone-on flights. Due to the anticipated reduction in flight time, straight-in approaches were used for the tailcone-off configuration.

Shortly after separation the crew performed a pitch sweep from +15 to -28 degrees. Surface inputs were initiated at two airspeeds, and a third set of inputs was made with the speedbrakes deployed to 50 percent. Landing was at 189 knots with a sink rate of 3.5 feet per second at touchdown. Crew response rated the handling qualities of the tailcone-off configuration equal to the tailcone-on configuration. Performance differences were noteworthy, especially the increased effect of modulating lift-to-drag ratio using both airspeed and speedbrake. All responses to surface deflections were well-damped. The crew also noted the improved braking during rollout, which reflected the success of brake rework between flights.

Free-Flight Five Highlights. The end of free-flight four marked the completion of the maneuvers required to fulfill the specific test requirements with the single exception of the requirement to demonstrate a runway landing. Free-flight five was specifically planned to accomplish this final objective. Separation and surface inputs for data runs went as planned. As the Orbiter neared the projected touchdown point, a pilot-induced oscillation (PIO) occurred for about seven to eight seconds resulting in a bounce from the first touchdown, and final touchdown 2000 feet down the runway. The PIO was terminated when the commander released the RHC and the software augmentation stabilized the vehicle. Comparison of cockpit cues and actual data revealed that the crew felt no sensation of rate buildup in the pitch channel although pitch oscillations of three degrees per second had occurred. The crew felt that small commands were being made, yet these inputs were in reality up to one-half the RHC deflection limit.

Test Results. A complete summary of ALT test results is included in JSC document number 13864. The following statements summarize the comparison of flight and predicted data for the tailcone-off configuration:

1. Lift and Drag data were within tolerance. However, L/D was four percent low at maximum L/D.

2. Elevon trim angle was as predicted. Normal force and pitching moment were individually in good agreement.

3. Yawing moment due to sideslip agreed well with predicted values. Rolling moment due to sideslip was generally less stable, sometime exceeding tolerance limits.

4. Aileron derivatives were within tolerance bands from the predicted values.

5. Rudder derivatives were typically within tolerance. In some cases, roll due to rudder deflection was slightly high.

Although the data extracted from the flight test showed good agreement, the uncertainties computed by the extraction program frequently exceeded the tolerance band of the predicted data. This must be construed as a reflection of the relatively short time for each data cycle (5-6 seconds) and the dynamics of the test conditions during the test pulses. The trends of the predicted values closely followed the predicted trends, however, and provide more confidence than the flight data uncertainties demonstrate.

The PIO from free flight five and the merging of events to recreate this situation were topics of study after the flight series were complete. Examinations of the external conditions such as airspeed, speedbrake setting, sink rate, etc., were meshed with crew inputs to duplicate the condition. Final studies coalesced to evaluate stick gain changes and deflection characteristics, as well as priority rate limiting within the vehicle software. Design changes have been made to modify the manual control characteristics for Orbital Flight Tests.

Dynamic effects due to the blunt aft end of the Orbiter generally were not as severe as anticipated. Instrumentation aboard the SCA and Orbiter showed pronounced increased buffet levels over the tailcone-on configuration, but did not degrade the crew or systems performance, nor affect the structural integrity of the vehicle.