The DP-2 Jet Lift Vertical Takeoff and Landing Aircraft Advanced Technology Demonstration Program

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ABSTRACT

DP-2 is a conceptual transport aircraft designed to have both vertical takeoff and landing and high subsonic speed conventional flight capabilities. The concept is based on a system of thrust deflecting cascade vanes located in the center fuselage, which provide both vertical thrust and control power during jetborne flight. When extended into the exhaust streams of two forward fuselage mounted turbofan engines the vane system can deflect thrust up to 105 degrees downward for vertical lift, and provide pitch/roll/yaw control without peripheral reaction controls. The DP-2 was conceived and initially investigated by DuPont Aerospace Company (DAC) in the early 1980's, and proposed to the government in 1987. The suitability of the concept for military applications was a subject of intense debate, eventually resulting in funding by Congress and a contract with the Office of Naval Research beginning in 1998. An all composite demonstrator aircraft, designated DP-1, was fabricated and began testing in 2000. The program culminated in a demonstration of steady hover while tethered to a test stand designed to simulate out-of-ground effect operations on Sep 30, 2007. Limited testing in ground effect was also conducted to explore the DP-1 hot gas ingestion. The paper will address the concept, issues with hover testing, test results, and suitability of the concept for military and civil missions.

INTRODUCTION

The DP-2 is an aircraft concept developed by Anthony DuPont of the DuPont Aerospace Company (DAC). The DP-2 aircraft as conceived by DAC is a transport aircraft asserted to be capable of vertical takeoff and landing, while carrying 50 passengers or a payload of 10,500 pounds with a range of approximately 5,000 miles and a top speed of approximately 545 knots. Proposed military uses of the aircraft include mounted vertical maneuver, sea based logistics support, search and rescue and special operations forces insertion / extraction. Potential commercial applications would include high speed, long range passenger service to airports with runways of less than 3000 feet, and specialized VTOL operations (isolated resorts, urban areas, oil platforms, etc).

Figure 1. The DP-2 concept aircraft conducting a troop insertion operation.

The DP-2 concept is significant for two reasons. First, it is one of two jet lift VTOL transport configurations to reach hardware. The first concept was the Dornier DO-31, which was extensively evaluated in the late 1960's. It is also the only jetborne VTOL aircraft to be designed to be controlled exclusively by primary exhaust deflection (i.e. no distributed reaction controls). The DP-2 concept is designed to generate large moments required to adequately control a transport aircraft

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with high moments of inertia and a large center of gravity envelope typical of transport aircraft. While the viability of this control concept remains to be demonstrated, it offers the obvious advantages of reduced weight, reduced internal volume, and reduced complexity when compared to a reaction control system.

The DP-2 concept was originally laid out by DAC in 1972. It was formally studied on paper in various forms by the Department of Defense (Air Force, Navy, and Advanced Research Projects Agency) at least four times between 1984 and 1991. Most of these studies focused on the suitability of the concept to meet the need for a long range special operations forces stealthy air infiltration / exfiltration system. In 1996, DAC did conduct a Defense Advanced Research Projects Agency (DARPA) funded full scale demonstration of its thrust vectoring system using the International Aero Engines V2500 engine.

Numerous independent assessments of the DP-2 concept were conducted by various DoD and Government agencies during the life of the programs. These studies were consistent in highlighting several significant risk areas, which could require major design changes to resolve. These include engine failure during vertical takeoff, adverse induced flow in ground effect (propulsion induced lift loss - suckdown), and natural propensity for hot gas ingestion. Other aspects of the concept which could compromise utility include jet blast effects, radar signature, limited range/payload, composite material use in the exhaust hot section, control instability and cross coupling, low directional control power, and noise.

An Advanced Technology Demonstration (ATD) project was conducted by the Office of Naval Research (ONR) from January 1998 to September 2007, with the goal of demonstrating the DAC thrust vectoring and control system (TVCS) vertical take off system and some associated innovative composite material construction. The ATD provided for fabrication and test of a 53% scale composite demonstrator aircraft, designated DP-1. Technical issues to be addressed by the ATD included (1) suitability of composite structure in the exhaust hot section, (2) vertical takeoff and hover performance and handling qualities, and (3) suckdown and hot gas ingestion in ground effect. Test facilities were fabricated and installed at the DAC facility at Gillespie Field, El Cajon, CA. Following vertical takoff and landing and hover tests, the DP-1 aircraft could potentially have been used to explore conventional flight, with transition to and from vertical flight. The DP-1 was designed for unmanned, automated flight control. This allowed for a higher risk development and test approach without risk of injury to a pilot.

THE DP-1 DEMONSTRATOR AIRCRAFT

The DP-1 is approximately 35 feet long and 31 feet wide, with an empty weight of 3800 lbs (figure 2). It has a conventional wing-body-tail configuration with two notable exceptions as a result of its unique configuration: it has a highly swept (42 deg) supercritical wing, and the two engines are mounted near the centerline in the forward fuselage. The engines are Pratt and Whitney Canada JT15D PWC 535A rated at 3,400 pounds of horizontal thrust each. The exhaust from the engines flows into a nozzle box, which contains a thrust vectoring control system (TVCS – described in the following section). The wing is an adaptation of the supercritical wing tested by NASA on a modified F-8 aircraft. The tail surfaces have symmetric supercritical airfoil sections. Wing and tail flight control surfaces (ailerons, elevator, and rudder) are incorporated for control in conventional flight.

Figure 2. The DP-1 aircraft on the elevated test stand (tethers removed).

The cabin was designed to be pressurized to sea level pressure when at a cruise altitude of 55,000 feet altitude to avoid passenger and crew discomfort. Given the very high thrust / weight inherent in a vertical takeoff aircraft, the airplane could potentially climb at a very rapid rate. Almost the entire airplane, including the TVCS, was constructed of carbon fiber composite; there are a few steel and titanium fittings in critical locations. As is typical for a proof of concept aircraft, the DP-1 features maximum use of off-the-shelf components from other aircraft. Landing gear were taken from a Beech Travelair, with the main landing gear having extended trunnions and side braces.

The flight control system was automated with a single flight control computer. The guidance and navigation system included a Systron Donner C-MIGITS Miniature Integrated GPS / INS Tactical System (using the inertial output only), with a Honeywell HMR2300 magnetometer and a NovAtel ProPak-G2 differential GPS receiver. Differential GPS was used to precisely locate the aircraft for automated hover. Control inputs were applied to the mechanical control system and throttles by Ultramotion linear electromechanical actuators with Animatics SM2320D SmartMotors. The TVCS cascade assemblies were actuated by a single hydraulic actuator, which was used to reposition the TVCS but was held fixed during hover attempts.

DP-1 THRUST VECTORING AND CONTROL SYSTEM (TVCS)

The TVCS was composed of two similar systems, one for each engine, each including six cascade vanes, a control box with four longitudinal and six lateral control vanes for generating control moments, and two horizontal doors. Figure 3 shows the overall propulsion system layout.

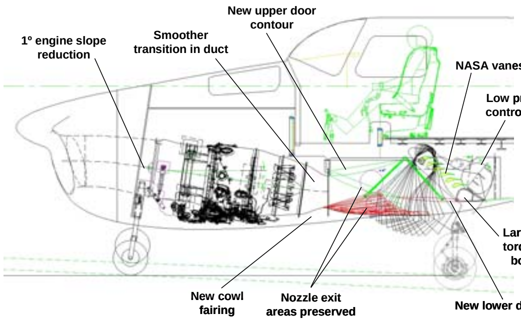

Figure 3. DP-1 Propulsion System, showing improvements made during the course of the ATD.

The cascade vanes deflect exhaust flow, and the doors move to convert the exhaust duct from vertical lift to conventional flow-through as the cascade system retracts. In jetborne flight, the lateral control vanes control roll, and the longitudinal vanes control pitch (when both sides are deflected in the same direction) and yaw (two sides deflected in opposite directions). The TVCS can deflect forward of vertical an additional 15 degrees for braking. Operation of the TVCS is shown in Figures 4 and 5.

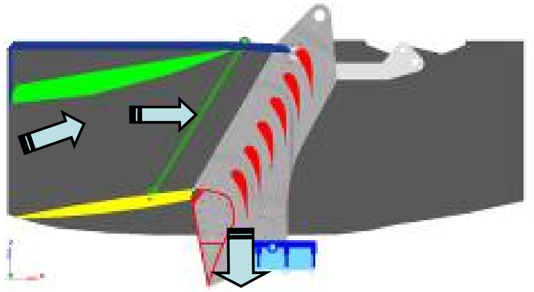

Figure 4. TVCS in hover position, with arrows showing engine exhaust flow direction.

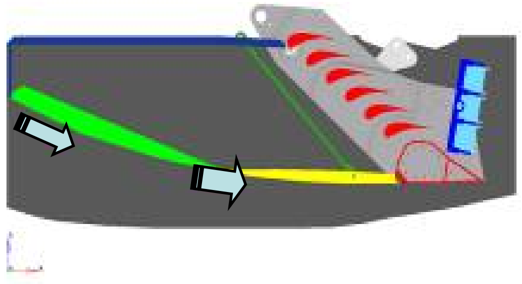

Figure 5. TVCS in Conventional Flight Position

With the location of the thrust vector beneath the aircraft center of gravity, the DP-2 is slightly unstable. In addition, in pitch and roll it exhibits dynamic behavior characterized by a control transfer function with a non-minimum-phase zero. When a hover lateral deviation is experienced, and pitch or roll is attempted to correct for it, the control box rotates causing both a pitch or roll moment, but also an initial thrust component pushing the aircraft farther in the deviated direction. This is not a disqualifying issue, but raised questions about how precisely hover could be maintained. It also raised a significant question which was to effect hover testing: that is, how much freedom of movement within tether limits would be required to allow for controlled hover, and were these tether limits restrictive enough to prevent significant damage if control anomalies were experienced during hover testing?

The TVCS could be adjusted to accommodate slight center of gravity (CG) changes while maintaining a level pitch attitude. This was accomplished by rotating the cascade slightly from the vertical position, with a corresponding counter rotation of the control box to bring the thrust vector back to vertical. In the DP-1 the allowable level attitude CG range is approximately 18 inches. This CG range is similar to comparable military type aircraft.

The TVCS was designed to be mechanically interconnected with the conventional flight controls, but during the conduct of the ATD flight tests the conventional flight controls were not used.

PERFORMANCE ANALYSIS

The Naval Air Systems Command's Advanced Aircraft Design Branch conducted an independent assessment of the Contractor estimated performance capabilities of the DuPont Aerospace DP-2 concept. The analysis was at a conceptual design level of fidelity, and was specifically focused on the useful load and radius of action of the DP-2. The analysis was done using in-house developed tools/methodologies and using standard assumptions for performance estimates of military aircraft.

The first calculation was the useful load of the DP-2, for an ambient condition below the engine lapse rate (< 86 F). The useful load was calculated by comparing the DP-2 thrust available to hover versus the DP-2 operational weight. The below methodology was followed for both calculations.

The thrust available to hover calculation started with the uninstalled thrust produced by the two V2533-A5 engines used in the DP-2. Then an installation loss was added, which accounts for inlet pressure recovery and bleed air loses. Next, a turning loss due to the DP-2 cascade vanes turning the flow from horizontal to vertical for take-off was subtracted. Finally, a thrust to weight allowance of 1.25 was applied as a conceptual design level allocation for sufficient thrust to cover propulsion induced lift losses, excess thrust to allow controllability during hover, and sufficient thrust to handle thrust losses from hot gas ingestion. The remaining thrust is the maximum available hover weight.

The first step in calculating the operating weight was to estimate the DP-2 empty weight. The empty weight was calculated using in-house methods, largely parametric in nature, to predict the component weight of the DP-2. A standard group weight statement breakout format was used. Several components that were significantly different than the parametric database were not estimated using parametric methods. Next, the operating equipment was added to the empty weight, resulting in the estimated DP-2 operating weight. The thrust available to hover was compared to the operating weight, and the difference between the two represents the DP-2 useful load.

Figure 6 presents the thrust available to hover and compared it to the operating weight. There was discussion about whether turning bleed off during vertical mode operations, as a way to increase performance, would be operationally acceptable. As such, data is included for both bleed on and off.

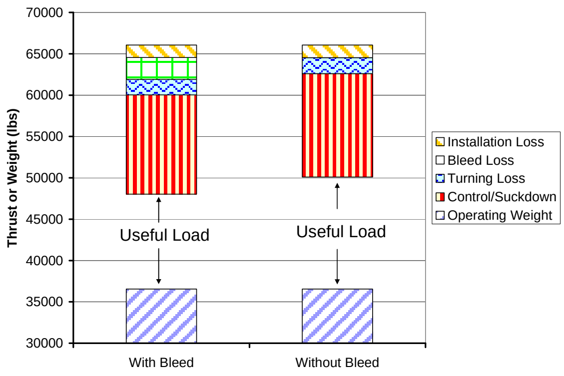

Figure 6. DP-2 Thrust Budget

The second aspect of the performance analysis was an assessment of the radius of action of the DP-2. This analysis factored in the aircraft drag, amount of fuel carried, engine specific fuel consumption (among other things) of the DP-2. It also considered engine lapse rate due to ambient temperature. Calculations were completed with no payload (all useful load carried as fuel- for maximum radius and a payload of 7,700 lbs (with the remaining useful load carried as fuel). The addition of payload at the expense of fuel caused the radius of action to decrease. The results of these calculations are presented in Figure 7.

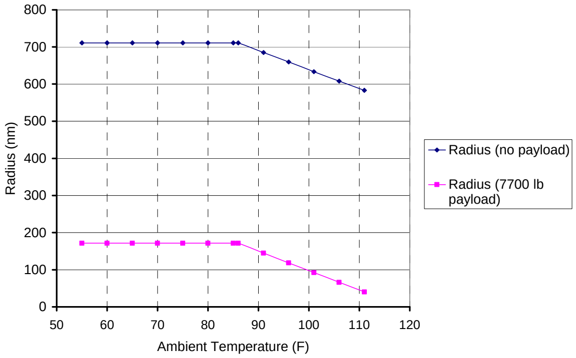

Figure 7. Ambient Temperature Effects on Radius of Action

MISSION SUITABILITY

Suitability for unimproved landing areas. One of the principal mission suitability issues for the DP-2 concept was whether or not it could be effectively utilized in the field. Since Short Takeoff and Landing (STOL) options are available (e.g. C-130), the DP-2 would need to have flexible VTOL capability to justify its development. However, the high velocity and temperature exhaust would preclude these types of operations except in limited, prepared sites due to exhaust impingement effects on unprepared surfaces and asphalt. Exhaust dynamic pressure for DP-2 is in the range of 1800-2000 pounds per square foot. From NASA data (reference 1) this dynamic pressure level would cause disturbance to sand and dirt well in excess of 200 feet altitude, and would disrupt dry sod during takeoff or landing. Exhaust temperatures exceeding 350 degrees F would not be compatible with asphalt.

Suitability for "fast rope" troop insertion and external loads. "Fast rope" troop insertion would be difficult, if not impossible, because of the high velocity exhaust. Figure 8 shows the forces exerted on a standing man under a DP-2, MV-22, or CH-53E in a 20 foot hover. The forces are much higher under the DP-2 than the MV-22 and CH-53E inside of a 50 foot radius. Side door distance from the exhaust would be approximately 5 feet, and even ramp distance of 40 feet from the exhaust stream would expose both the loose ropes and exiting personnel to high force and buffeting. It is likely that suspended ropes would gyrate erratically, extend out at a high angle or require ballast weight, and that ground footing would be very difficult, making these operations hazardous. External load carriage would not be possible, given the exhaust location aligned with the CG, under which the load would be carried.

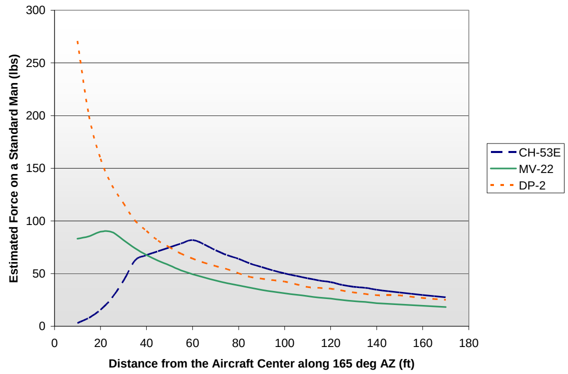

Figure 8. A Comparison of the Estimated Force on a Standard Man vs. The Distance from the Aircraft Center along 165 degree Azimuth for the CH-53E, DP-2, and MV-22. (Note: Figure 8 was generated by conceptual design level of fidelity downwash/outwash velocity and force prediction tool. Prediction tool is conservative (when compared to flight test data, it may over predict velocities and forces). All three A/C data are for a 20 ft hover above the ground (wheel height) on a SL/STD day. MV-22 weight 45,000 lbs, CH-53E weight 56,000 lbs, and DP-2 weight 50,087 lbs.)

DP-1 TEST APPROACH

An issue in any VTOL aircraft test program is how to safely test hover and transition between conventional and hovering flight (hereafter referred to as just "transition") safely. One approach would be to conduct simpler conventional flight first, and gradually approach transition and hover at a high altitude which would allow for safe recovery from any anomalies. However, limited funding and limited company experience, and the fact that the technical innovation of the DP-2 concept was in its hover capability dictated a very conservative approach in the case of the DP-2 program. Therefore the decision was made to conduct tethered hover out of ground effect (HOGE) first. Subsequent envelope expansion would have been to examine liftoff and hover in ground effect (HIGE) and low altitude untethered hover maneuvers. In an additional risk reduction measure, all test operations where flight was possible were conducted unmanned, using an automatic control system with close external monitoring.

Another cost reduction measures was to not employ a full hardware-in-the-loop (HIL) flight simulation process. The latter decision was later to contribute to some major program setbacks.

TESTING TVCS FORCES AND MOMENTS

Measurement of the forces and moments generated by the TVCS was attempted early in the program on the elevated test stand. However, vibration of the test stand rendered the accelerometer readings totally unusable. In order to calculate forces and moments, strings were attached to the control boxes, and angular deflections observed during control inputs. This was considered a reasonable approximation for use in hover, but no measurements were made in cascade positions other than 90 degrees. More precise, direct measurements of forces and moments were desired at all cascade and control box positions, in order to provide inputs to a simulation of operations during both hover and transition. At the time of program termination, a rigid test stand had been designed and partially constructed for this purpose, as shown in figure 9, but not utilized.

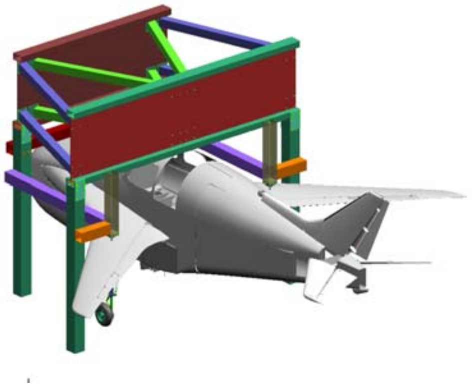

Figure 9. Force and Moment Measurement Test Fixture

HOVER OUT OF GROUND EFFECT (HOGE) SUMMARY

HOGE tests were conducted on a test stand that was elevated 10.5 feet above a concrete ramp. The area beneath the engine exhaust and the forward inlets was covered by a steel grating designed to approximate conditions in free air away from the ground. The test stand configuration is shown in figures 10 and 11.

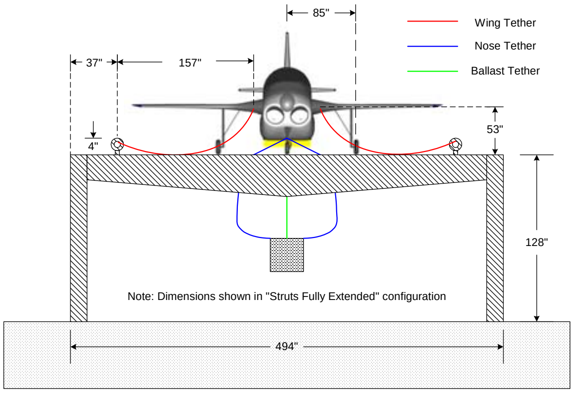

Figure 10. HOGE Test Stand Arrangement, Front View

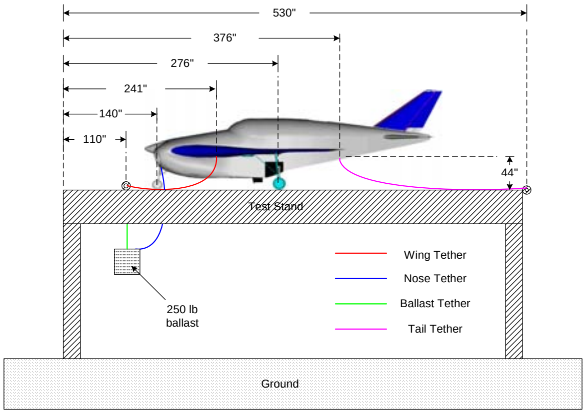

Figure 11. HOGE Test Stand Arrangement, Side View

Tethers were attached to the aircraft at four points. Because tether impact could cause major deviations in attitude rates and lateral motion, “virtual tethers” were implemented in the autopilot. Encountering a virtual tether would cause the aircraft to neutralize control inputs and reduce throttle to flight idle, aborting the hover attempt. The virtual tether limits were set at:

Horizontal motion of 2 feet per second
Vertical motion of 1 foot per second
Horizontal deviation of 3 feet
Height of 3 feet above the test stand

Forty-nine hover tests were conducted during the July – October 2006 time frame with the latest DP-1 aircraft configuration. All these attempts were aborted within 3 or 4 seconds after engagement of the autopilot. With no clear or consistent cause, explanations for the inability to hover were evaluated as follows:

Ground effect. Data appeared to indicate that there was some residual ground effect, even on the raised test stand. It was expected that due to the aircraft configuration, suckdown effect would be greater on the forward fuselage due to its larger horizontal flat plate area near the exhaust stream, and lower location, relative to the aft fuselage, and that this effect would dissipate with height. Existing pressure instrumentation could not be used to arrive at a direct analytic measure of suckdown level, but DAC observed about 1 degree of pitch control angle change for trim with each foot of altitude above the test stand. Therefore a pitch trim bias was inserted in the flight control laws to counter a nose up pitch as altitude increased.

Control system hysteresis. Significant attention was paid to elimination of hysteresis in the TVCS mechanical control systems. Throttle stiction and backlash, which had initially been a problem, was corrected by mounting the throttle actuator directly to the hydraulic pump pad on the accessory section of the engine, very close to the engine throttle input.

Nose tether drag. At one point it was suggested that the nose tether could exhibit drag as it paid out during liftoff, unbalancing the aircraft in hover. Smooth tether guides were added with little apparent effect.

Insufficient yaw control. TVCS control authority was limited to minimize risk of overcontrol during hover attempts. However, this resulted in very limited yaw control power. The yaw axis was the least powerful, because the moment arm between the two control boxes was much shorter than the CG-to-control box arm for pitch and roll. A number of hover attempts were aborted due to excessive yaw. This effect could only be controlled by limiting tests to conditions with little or no crosswind.

Engine response. Ability of the turbofans engines to respond quickly enough to achieve and maintain hover within the altitude band allowed was examined. The engines were tested for response to commands within a control range of plus/minus 1 % N1, and the bandwith of the actuator and engine system determined to be 2.2 Hz. In simulation this was adequate to maintain hover height of 1.5 feet within plus / minus 3 inches. Concern was expressed as to initial capture of hover height because slow liftoff could induce deviations through the landing gear, and rapid liftoff could cause the virtual tether limits to be exceeded. The procedure developed was to set thrust at calculated liftoff thrust (approx. 90% N1) minus 2%, engage the autopilot altitude loop, then at 3 inches above liftoff, engage the position control loops. Several altitude loop initial ramps were tried.

Liftoff with minimal induced lateral motion or attitude rate. A great deal of effort was expended to ensure that the CG was precisely located over the thrust vector, and the thrust vector was exactly vertical, prior to a hover attempt. The main wheel brakes were also locked to avoid rolling prior to liftoff. The TVCS autopilot position loops were not engaged until 3 inches above liftoff to prevent wheel bounce from contaminating the autopilot control calculations. Any deviations arising from CG variation could build up during liftoff, increasing the difficulty of achieving hover within the confined test limits. A large number of liftoffs were conducted to calibrate the aircraft CG to within ¼ inch to lift off in a precisely balanced manner. In addition, all tests were conducted during no-wind conditions.

Alternate tether systems. Tether systems that could safely allow greater freedom of movement while controlling risk were repeatedly examined. Top-tethering appeared to offer the greatest promise in this regard, but would have been prohibitively expensive to design and implement.

Adequacy of the flight control laws. The basic architecture and gains of the autoFCS were relatively straightforward and appeared to be adequate. Hover test data were compared to the simulations and extensively analyzed. Because no hover attempts lasted more than 8 seconds and / or contained a full converging correction cycle (correction / countercorrection), it was arguable as to whether or not the simulation adequately replicated or predicted the test results. Extensive testing of the control loops was also conducted, within the simulation environment, and no deficiencies discovered.

HOGE hover tests were resumed in September 2007, after a period of extensive analysis and implementation of corrections. Although improved performance in altitude hold was demonstrated, as of 29 September no hover exceeded 8 seconds prior to abort.

An attempt to incorporate compensation for CG shift with fuel burned was initiated. At fuel weights used for hover test (about 50 lbs), the CG shifted aft about 0.011 inches per pound of fuel burned, or about 1/3 inch total in a 30 second hover. This would require about 1 ½ degree of pitch control compensation, which could add to rearward drift (which was frequently noted). Therefore a timed adjustment to pitch trim was added to the autopilot logic. This adjustment passed the autopilot off-line simulation verification process and was loaded onto the test aircraft. However, when the autopilot was actuated on the aircraft, the pitch control moved to the full nose down position in 5 seconds and would no longer respond. This control movement was about 20 times faster than planned, so a timing error was evident. A detailed investigation of the actual machine generated code for the autopilot showed that the time step used in the fuel burn trim compensator was 0.2 seconds instead of the 0.01 second sample time that the pre-flight simulation model had used. Furthermore, all the integrators throughout the control law code were found to use 0.2 seconds integration time steps instead of the intended 0.01 seconds. This error resulted from the MATLAB Real Time Workshop substituting its default value for sample time, and was corrected by explicitly coding the sample time. The fact that there was no HIL simulation facility available contributed to the delayed discovery of this error. None of the integrating functions in the flight control system, prior to the fuel burn integrator which was dependent only on time, could be observed or tested independently outside of flight tests. Isolation tests on control functions in simulation did not reveal the problem, because it only occurred during translation to flight software. Comparisons between test and simulation were made between vehicle location, attitude, rates and accelerations, and these were inconclusive because functions could not be isolated. When the error was simulated in the autopilot code, the simulation closely matched the flight data for the first time. When the flight control code was corrected, two extended stabilized hovers of 45 seconds were finally achieved on the planned last day of flight tests, September 30, 2007.

Figure 12. DP-1 Aircraft in Tethered Hover

OPERATIONS IN GROUND EFFECT

Hover attempts in ground effect were intermixed with HOGE attempts at several points in the program. The objectives of these tests were to evaluate engine operation, and determine the extent and nature of suckdown effects. It became apparent early in these tests that engine operation was greatly compromised, as engine stalls were consistently experienced at less that 80% N1 RPM. Laser light sheet tests were conducted, with the assistance of NASA Glenn Flight Research Center personnel, to determine the nature of the airflow which might be causing engine inlet instability. These tests showed the presence of vortices which developed between the ground and the inlet just prior to stall occurrence. It was theorized that inlet instability was the result of vortex-induced flow anomalies, rather that hot gas ingestion (HGI), although data were inconclusive on this. Tests were then conducted with various fence, deflector, and nose wheel configurations to see if these vortices could be reduced or eliminated. Configurations tested included 5 and 10 inch nose cowl fences, boxes around the nose wheel, flat plates under the nose cowl, nose gear with wheel pants, and nose wheel removed. Figure 13 shows one of the fence configurations tested.

Figure 13. DP-1 with 5 inch cowl fence

All of the tested configurations experienced engine stalls in the 70 - 80% N1 RPM range, which was well below liftoff thrust level (approximately 90% N1 RPM) even in the lightly loaded test configuration. It was clear from these tests that the DP-2 design would have to be significantly modified to allow liftoff and hover in ground effect.

ENGINE FAILURE ANALYSIS

Another major issue with the DP-2 concept was one engine inoperative (OEI) performance and handling. On the one hand, directional control in hover or slow speed flight (below rudder aerodynamic control effectiveness) cannot be maintained by the TVCS with only one engine operating. Therefore some sort of emergency backup thrust vectoring reaction control would have to be provided, with its associated weight and performance penalties. On the other hand, the aircraft is incapable of autorotation. Therefore, the aircraft would be limited to operations in which a landing area was available under the acceleration path to the point at which conventional flyaway could be achieved on a single engine. The calculated height-velocity curve for DP-2 engine failure is shown in figure 14. Engine failure inside the enclosed area would result in a ground strike of greater than 6 feet per second.

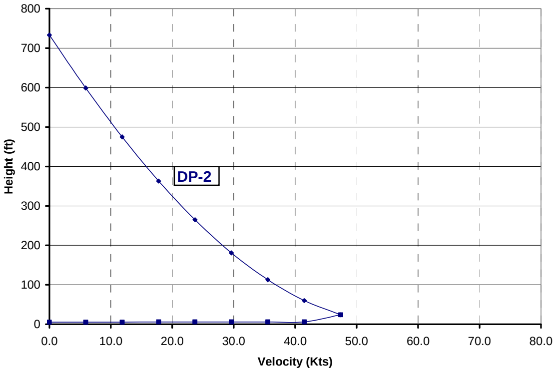

Figure 14. DP-2 Height-Velocity Curve with 2 second pilot delay before reacting to OEI

This landing area requirement could be sufficient to reduce or eliminate the advantage of the DP-2's VTOL capability relative to that of more cruise-efficient STOL aircraft in civil operations. In military operations, it's not clear how much operational risk could be traded for VTOL capability in critical missions. This issue would require further exploration but has to be viewed as potentially prohibitive.

COMPOSITE MATERIALS

The DP-2 concept, and the DP-1 test aircraft, incorporated extensive use of composites. The airframe structure was manufactured out of two types of composite material systems, one for the basic airframe and the other for the TVCS area that requires exposure to high temperatures. The airframe structure was mostly manufactured using a fiberglass reinforced polyimide honeycomb (HRH-327) and graphite and cyanate ester prepreg skin (LTM45) configuration. All of the structure was vacuum bag/oven cured instead of using an autoclave. Major joints of the airframe were bonded together using film adhesive, minimizing fastener use. The material choices would be a concern if the concept were to be operated in a maritime environment, but were usable in the test article to prove the concept.

The major risk with composite materials was in the exhaust hot section. The nozzle box in which the TVCS was mounted, the cascades, the deflection doors, and the control surfaces were manufactured from composite material. Several delaminations and failures of nozzle box honeycomb sandwich panels were experienced during the course of testing. Eventually all honeycomb sandwich panels in the nozzle box, cascades, and doors were replaced with a coreless construction, using skins supported by an internal truss structure. Material used was graphite and cyanate ester prepreg matrix material (Advanced Ceramics Group LTM110).

NASA Glenn Flight Research Center developed a Computational Fluid Dynamics (CFD) model of the engine exhaust. The temperature profile of the engine exhaust at the TVCS cascades is shown in figure 15, and the central temperatures are well in excess of the maximum desired for the LTM110 composite material. CFD analysis of an extended tailcone were also conducted to see if the maximum temperature in the area of the cascades could be reduced. This analysis showed a potential reduction of peak temperature to approx. 1020 R, but with an undetermined thrust reduction.

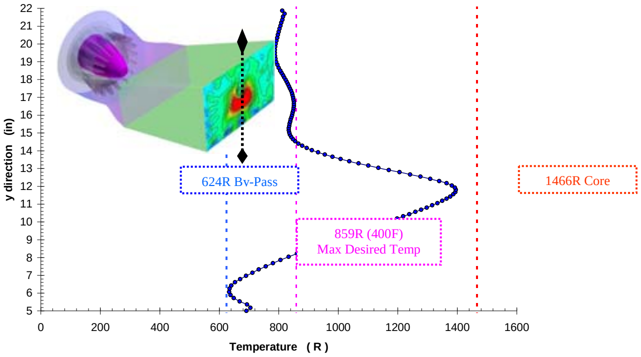

Figure 15. CFD Vertical Temperature Profile at the TVCS Cascades

No catastrophic failures of the cascade vanes were experienced during the course of the program. However, a cascade vane with 50 hrs and 41 minutes of run time experienced some erosion on the leading edge, and bulging / delamination on the underside. In light of the high exhaust temperature and wear experienced by the composite cascade vanes, they are unlikely to be suitable for military or commercial operational use.

CONCLUSIONS

Major conclusions that can be drawn from the DP-2 program are:

1. The TVCS design is capable of efficiently turning the exhaust flow, and shows potential to be able to control a transport aircraft in hover.
2. The design is not suitable for operation in ground effect due to engine instability. This

instability could be due to vortex generation and/or hot gas ingestion.

3. The TVCS cannot by itself control the aircraft in yaw in the event of engine failure at low speed. Provisions for a backup system are required.
4. TVCS cascade vanes fabricated from carbon epoxy composite material show excessive wear and will not be acceptable for operational use.
5. Utility of the DP-2 VTOL capability is limited due to the need to have a landing option, in the event of engine failure, during acceleration to wingborne flight unless increased operational risk is accepted by the user.
6. The design does not appear to be suitable for use on unprepared surfaces or asphalt, for external loads, or for “fast rope” deployment of troops.
7. Performance will likely be substantially less than the DAC claims, principally due to optimistic weight assumptions. The lack of a database of propulsion induced forces and moments, typically derived from small-scale test data, increases the risk to performance and flying qualities estimates.

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