THE STOL MANUEVER TECHNOLOGY DEMONSTRATOR MANNED SIMULATION TEST PROGRAM

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ABSTRACT

The STOL Maneuver Technology Demonstrator (S/MTD) simulation is a high fidelity pilot-in-the-loop motion base simulation at Wright Patterson Air Force Base Flight Dynamics Laboratory (FDL). The simulation was used to evaluate takeoff, landing, and air-to-air tasks before first flight of the S/MTD aircraft to improve aircraft flying qualities, conduct engineering research, and insure safety of flight. 208 hours of pilot-in-the-loop evaluations were conducted. This paper describes the simulation hardware, modeling, test approach/results of the Pilot Vehicle Interface (PVI), flying qualities and aircraft failure evaluations in the STOL landing (SLAND) flight control system mode. The SLAND evaluation was part of a complete validation of the operational flight program control laws conducted at the FDL simulation facility.

BACKGROUND

The S/MTD program objective is to investigate, develop, and validate technology areas related to providing current/future high performance fighters a Short Takeoff and Landing (STOL) capability without undue weight or performance penalty. These technology areas are: 2-dimensional thrust vectoring and reversing exhaust nozzles; Integrated Flight/Propulsion Control (IFPC) system; rough/soft field STOL landing gear; and advanced PVI.

The STOL demonstrator aircraft is an F-15B airframe modified with thrust vectoring and reversing nozzles, rough/soft field landing gear, and canards. The aircraft contains a F-15E crew station and basic avionics package which includes central computer, ring laser gyro inertial navigation system, APG-70 Synthetic Aperture Radar (SAR), LANTIRN navigation Forward Looking Infrared Radar (FLIR) pod.

The Series V+ S/MTD simulation is the last of a five series developmental simulation test program completed at FDL and McDonnell Aircraft (McAair) simulation facilities. The simulations were updated as wind tunnel data became available and control laws developed. The aircraft models used were delivered to the USAF from McAair in accordance with contractual requirements. The Series V+ simulation evaluation exercised all Operational Flight Program (OFF) flight control system modes in air-to-air tracking, landing and takeoff tasks.

SIMULATION HARDWARE

The S/MTD simulation computer network is built around two SEL 32/77s, a SEL 32/27, and a SEL 32/97. These are 32 bit digital machines with high speed, real-time and scientific computing capability. A generic block diagram of the simulation is shown in Figure 1. The aerodynamic, flight control system, actuator models, landing gear model, Head Up Display (HUD) algorithms, and environment software were updated 40 times per second. The heads down display algorithms and propulsion model were updated 20 times per second.

FIGURE 1: Generic Block Diagram

SIMULATOR

All experiments were conducted in the Large Amplitude Multi-Mode Aerospace Research Simulator (LAMARS). The LAMARS consists of a single-seat cockpit installed in a 20 foot diameter dome attached to the end of a 30 foot beam. The combined beam/dome movements result in a five degree-of-freedom motion system which can generate angular velocities of up to 60 degrees per second, linear velocities of up to 13 feet per second, and instantaneous accelerations of up to 3 g's.

VISUAL DISPLAY SYSTEM

The visual scene generated for the landing evaluations is from an American Airlines/Redifon 1500:1 scaled terrain board system. The viewing area is continuous in heading and roll, but limited in pitch to +24 degrees to -47 degrees and is

displayed in the LAMARS as a 60 degree diagonal field of view. The runway area on the terrain board was modified with an overlay portraying bomb damage to establish five 50 x 1500 foot Minimum Operating Strips (MOS's).

CREW STATION

The LAMARS cockpit represents to the extent possible the forward crew station of the S/MTD aircraft (Figure 2). A F-16 LANTIRN Wide Field Of View (WFOV) HUD was used instead of the F-15E WFOV HUD. Both HUD's have a 20 degree by 30 degree field of view. Two 6 inch Multi-Purpose Displays (MPD's) provided heads down display information. The S/MTD center stick and rudder characteristics were modeled by a McFadden three axis feel system. Toe brakes with the standard F-15 force-feel characteristics and S/MTD throttle quadrant with a spring loaded thrust reversing region was also provided.

FIGURE 2: Forward Crew Station

SIMULATION MODELS

AERODYNAMIC

The aerodynamic model consists of 250,000 data points. 125,000 points are used to model low speed jet effects and ground effects data. All the data was obtained through wind tunnel tests supported by the S/MTD program. The flight envelope for the data consists of: 1) 0 to 50,000 feet altitude; 2) 0 to 2.5 Mach; 3) -4 degree to 90 degree angle-of-attack; and 4) -30 degree to 30 degree side slip.

FLIGHT CONTROL SYSTEM

The digital fly-by-wire IFPC system is the FORTRAN version of the Operational Flight Program (OFP) control laws. The control laws are designed to functionally integrate all control effectors which includes aerodynamics surfaces, engine thrust, thrust vectoring/reversing, nose wheel steering and braking.

The IFPC system has several modes to enhance flying qualities and reduce pilot workload. The IFPC system allows in-flight selection of these modes.

The Conventional mode is the only mode which does not exercise the reversing/vectoring

technologies provided by the 2-dimensional engine nozzles. This is a nozzle failure backup mode and designed for level 1 flying qualities.

The Cruise mode is a flaps up thrust vectoring/reversing mode to provide optimal flight path control.

The Combat mode is a flaps up thrust vectoring/reversing mode to provide optimal attitude control for air-to-air tracking.

The STOL mode is a flaps down thrust vectoring/reversing mode to maximize performance for takeoff and normal approach. It is designed for angle of attack control along with precision fuselage pointing for takeoff.

The SLAND mode is a flaps down mode which utilizes the thrust reversing vanes to maximize performance on final approach. The engine goes to military power and the main nozzle is closed. The aircraft speed is controlled by the thrust reversing vanes which allows for optimal speed control (no engine spool-up delay). The aircraft speed is also held constant for a given throttle setting and the IFPC system decouples airspeed and pitch attitude. The SLAND mode defaults to STOL mode by advancing the throttle past the military power detent.

The STOL ground handling mode provides minimum stopping distance and enhance ground handling capabilities due to thrust reversing capabilities. The mode is engaged from SLAND and STOL modes at weight-on-wheels and wheel spin-up and disengages to STOL mode by advancing the throttle past 35 degrees for aborted landings.

PROPULSION

The propulsion model is representative of the Pratt and Whitney F100-PW-220 with a 2-Dimensional (2-D) nozzle and nozzle controller. The left and right engines are modeled separately to provide differential thrust. The 2-D nozzle is shown in Figure 3 and allows for thrust vectoring/reversing. The Conventional mode allows for augmented and non-augmented operation optimized at all flight conditions. The aft-vectoring mode allows vectoring from -20 degrees to +20 degrees. The SLAND and reversing modes rotate upper and lower vanes -2 degrees (stored position) to 135 degrees (maximum reverse thrust position) to provide forward or reverse thrust.

CONVENTIONAL THRUST CONFIGURATION

VECTORING CONFIGURATION

VANE CONFIGURATION

FIGURE 3: 2-Dimensional Nozzle

LANDING GEAR

The digital S/MTD gear model represents the Cleveland Pneumatic Corporation landing gear. The landing gear is modified to allow for a 12 fps sink rate and rough field operation. The anti-skid, autobrake, toe brakes and nose wheel steering are also modeled.

ATMOSPHERIC DISTURBANCE MODELS

The low altitude atmospheric disturbance model is defined in MIL-F-8785C, Military Specification Flying Qualities of Piloted Airplanes. Specific components used include steady state crosswind, wind magnitude shear, wind vector shear, and random turbulence.

HUD DISPLAY FORMAT

The gear down HUD format is shown in Figure 4. The navigation steering mode selected is Autonomous Landing (AUTL). The HUD format features the following unique symbology.

The MOS is a 50 x 1500 foot representation of the landing strip. The MOS is drawn with respect to the designated runway point and heading.

The E-Bracket is used for speed control. The E-Bracket (size is +1 to -1 degrees) is drawn with respect to the velocity vector. When the aircraft is at the referenced Angle-Of-Attack (AOA), the E-Bracket's center is in line with the velocity vector's wing tip. If the aircraft AOA is above the referenced AOA, the E-Bracket would be below the velocity vector. Therefore, the pilot would add power by moving the throttle forward (a fly-from command).

The flare cue provides information to flare the aircraft on a -2 degree glideslope. The flare cue appears when the aircraft radar altitude is less than 200 feet. The flare cue aligns when the glideslope is -2 degrees and is below the velocity when the glideslope is less than -2 degrees.

The AUTL steering carets are fly-to commands driven with respect to the velocity vector. The carets are driven in elevation to obtain the desired -3 degree glidepath and are driven

in azimuth to steer the aircraft to the final approach ground track. The carets also rotate to indicate a desired aircraft bank angle to get on radial.

The AUTL steering needles can be selected instead of the carets. The needles are fly-to commands and provide the same information as the carets but in a different format. The elevation needle is drawn horizontally and is fixed in azimuth to the tail of the velocity vector. The elevation needle is driven in elevation with respect to the velocity vector to provide steer commands to obtain the -3 degree desired glidepath. The azimuth needle is drawn vertically and is fixed in elevation to the wing tips of the velocity vector. The azimuth needle is driven in azimuth to provide a steer command to obtain the desired final approach ground track. The elevation and azimuth needles are limited to the end of the other needle.

In the caged velocity vector mode, a ghost velocity vector appears and displays the aircraft flight path. The solid velocity vector is caged in azimuth to the center of the HUD and the elevation drive is not altered. The E-Bracket, AUTL steering carets/needles, pitch ladder and flare cue are drawn with respect to the solid velocity vector. This allows for easy interpretation of these symbols, when the uncaged velocity vector is displaced in azimuth (i.e. due to high crosswinds).

WARNING/CAUTION/ADVISORY SYSTEM

The master caution light and aural warning (Figure 5) notify the pilot that a failure or caution exist. The master caution light turns off when the master caution switch is depressed or the fault is corrected. The pilot can determine the type of failure/caution using the master caution legend. The master caution legends overwrite the display selected on the right MPD. Backup to the master caution legends are the caution/advisory panel lights. The pilot can determine IFPC failures or monitor effector positions by selecting the IFPC status display (Figure 6) on either MPD. Failure information is provided on a per IFPC channel basis (1, 2, 3 or 4) for each IFPC component. The IFPC component is completely failed

FIGURE 4: HUD Format With Gear Down/AUTL Steering

when the rectangle adjacent to the component is filled. IFPC effector positions are displayed with "U", "D", "L" or "R" appended to the deflection in degrees. This indicates surface trailing edge up, down, left or right respectively (except for canards which is with respect to leading edge). The left stabilator in Figure 6 is deflected 30 degrees trailing edge up.

FIGURE 5: Master Caution And Caution Panel

FIGURE 6: IFPC Status Display

SLAND MODE LANDING EVALUATIONS

TASK DESCRIPTION

For the landing task the pilots were initialized at 150 KCAS, 1000 ft above ground level (AGL), approximately two nautical miles from touchdown, with flaps and gear down. A MOS was drawn on the main runway in black. At each end of the MOS was a touchdown box consisting of a white block figure-eight 20 feet wide and 60 feet long (see Figure 7). The touchdown aimpoint was in the center of the middle crossbar. The task was to slow to 119 KCAS and follow the command steering guidance on a 3 deg glideslope down to the

touchdown point. The pilot was instructed not to command a flare but to let the aircraft flare naturally as it entered ground effect. During the rollout the pilots tried to keep the aircraft on the MOS and stop it before it reached the end. Familiarization landings were made with no crosswinds on a dry runway. Then crosswind landings began at 15-knots, after which they were built up to 30-knots by 5-knot increments. This familiarization procedure was repeated on wet/icy runway. Both wind and runway conditions were randomly evaluated during the formal test phase.

FIGURE 7: Touchdown Box

The steady winds were all crosswinds perpendicular to the runway heading. Wind speeds used in the evaluations were 0, 15, 20, 25, and 30 knots. The wind direction could be either from the right or from the left.

The scale lengths of the random turbulence were taken directly from Paragraph 3.7.3.4 of MIL-F-8785C. This paragraph also specifies that the rms of the w-gust component should be one tenth of the wind speed at 20 feet above the ground. Separate effects of crosswind and turbulence were evaluated along with lower levels of turbulence with a given crosswind. The rms intensities of the w-gust component used in the evaluations were 0.0, 1.0, 2.0, 2.12, 2.83, 3.54, and 4.24 ft/sec. Table 1 contains the combinations of crosswind and turbulence used.

TABLE 1: Crosswind and Turbulence Combinations

$U_w \backslash \sigma_w$	0.0	1.0	2.0	2.12	2.83	3.54	4.24
0	32						
15	17	9		47			
20	11	7		6	43		
25	3	5	4		10	34	
30	16	14			21	18	16

For the pilot ratings, the landing task was divided into three sub-tasks: approach, transition, and rollout. The approach sub-task went from initialization to 200 feet AGL and the pilot's task was to follow the command steering guidance down a 3 deg glideslope. The transition sub-task went from 200 feet AGL to touchdown and the task was to land as close to the designated aimpoint as possible. The rollout sub-task began immediately after touchdown and went to the end of the simulation run. The task was to keep the aircraft within the MOS boundaries. The pilots gave a Cooper-Harper (CH) rating for each sub-task of the landing based on adequate and desired performance criteria that had been determined during the familiarization phase. For the approach sub-task, adequate performance was defined as keeping the velocity vector "boxed" by the command steering bars (i.e. keeping the flight path marker within the length of the steering bars though not necessarily on them) and the airspeed within 10 knots of 119. Desired performance was defined to be keeping the velocity vector within half the length of the command steering bars and airspeed within 3 knots. For the transition sub-task, adequate performance was to land on the MOS. Desired performance was defined to be landing in the touchdown box. For the rollout sub-task, adequate performance was defined to be staying on the MOS. Desired performance was to steer down the centerline within half the width of the MOS. There was no criterion on rollout distance since the pilots were using autobraking, but rollout distances were recorded.

ATMOSPHERE COMMENTS

Pilot opinion of the turbulence indicated that it was fairly representative of disturbances encountered in atmospheric turbulence with some qualifications. First, the pilots felt that the turbulence levels as defined by MIL-F-8785C were too high. What MIL-F-8785C defined as moderate turbulence (u-gust rms = 5 to 10 ft/sec) felt more like severe turbulence to them. They felt the moderate turbulence started somewhere between 3 and 4 ft/sec rms. The pilots also noted that the turbulence seemed to be mostly pitch and speed disturbance. There was relatively little lateral or rotational disturbance. Another problem with the turbulence model was the fact that the u- and v-gust intensities increased as the aircraft lost altitude. The pilots particularly noticed the increase in u-gust and felt that this effect was opposite of what they normally encountered. One other comment was that the turbulence felt sinusoidal, almost predictable. Later analysis of time histories showed that the "white noise" generator of the computer was cycling at periods of 6.4, 12.8, or 25.4 seconds. So on a given run, a pilot would see the same sequence of "white noise" over and over again. Since the turbulence power spectral densities were changing as speed and altitude changed he would not see exactly the same turbulence over and over during the run, but it would certainly seem cyclical. The random number sequence and period was different from run to run. Despite these comments, the pilots felt that the disturbances generated by the turbulence model were

turbulence-like in nature and added realism to the landing task.

APPROACH SUB-TASK

The most important factor affecting approach performance was the turbulence. Turbulence increased the workload in both tracking and speed control, eventually affecting performance. Crosswinds had a minor affect on tracking workload. Figure 8 shows the Cooper-Harper ratings for the approach task as a function of turbulence. Performance was judged on ability to track the steering cues.

FIGURE 8: Approach Task CH Ratings

With no turbulence the pilots consistently achieved desired performance. For these cases, there was no appreciable difference in performance with crosswinds. Pilot comments indicate that the task was easy, there were no deficiencies in aircraft handling, and pilot compensation was not a factor. The pilots were able to keep course and glide path steering well within desired criteria. The pilots felt that the speed hold was an excellent feature that dramatically reduced workload. Once the speed was set the pilot could concentrate entirely on course and glide path control. The only negative comments were for getting on speed initially. The pilots did not like using the E-bracket to set speed. They felt it was too sensitive and tended to induce a speed Pilot Induced Oscillation (PIO). They preferred to bring the speed down in small increments, checking against the digital airspeed display instead of the E-bracket. But, with no turbulence, this was a minor deficiency, and the pilots felt it was a display problem instead of a problem with speed response. Cooper-Harper ratings were all Level 1 (2's and 3's) for both the no-crosswind and crosswind cases (all levels) without turbulence (see Figure 8).

In the lowest turbulence, the approach sub-task was still easy, with no serious deficiencies, regardless of crosswind. Desired performance was almost always achieved and the ratings were mostly Level 1. The pilots described this level of

turbulence as an annoyance. It increased the workload slightly, but the pilot compensation was basically just a matter of averaging out the effect of the turbulence on the steering cues.

In the medium turbulence settings (w-gust rms = 2 to 2.83 ft/sec), the major deficiency was higher workload due to speed and pitch changes caused by the turbulence. The pilots still achieved desired performance quite frequently, though adequate performance was more common. The pilots assigned Level 1 and Level 2 ratings. The pilots mentioned that this level of turbulence tended to get them into low-frequency pitch oscillation if they pursued the pitch steering cue too closely. (This was due to the cyclical nature of the random number generator.) It was not a threatening oscillation, but the pilots noticed it and found it annoying. At w-gust rms = 2.83 ft/sec, the pilots found the E-bracket to be useless. It responded so much to the turbulence that it was frequently giving incorrect cues.

At the higher turbulence settings (w-gust rms = 3.54 and 4.24 ft/sec) the speed and pitch changes due to turbulence were too large for desired performance. Still the pilots usually achieved adequate performance, and controllability was never in question. The pilots usually rated these cases Level 2 which is consistent with MIL-F-8785C.

Crosswinds increased the pilots' workload because of the need to perceive and cancel drift rates caused by the wind. The pilots noted the increased workload in their comments but it did not seem to affect their performance, and was not serious enough to affect their ratings as much as the turbulence.

TRANSITION SUB-TASK

The primary problem in the transition task was a simulator problem, not an aircraft response problem. Like many ground-based simulators, the LAMARS visual scene suffers from "tunnel vision" and lack of depth perception. In addition to these problems the visual system has poor resolution. The pilots had trouble identifying the MOS from their initial position, and they could not see the aimpoint until they were about 50 feet AGL. Since transition to touchdown is a very vision-oriented task, the limitations of the LAMARS visual scene severely degraded the pilots ability to do the task. In fact, one of the pilots decided that the visual problems were so intrusive that he could not accurately rate the task.

To reduce the impact of this problem on the task ratings the pilots were instructed to base their ratings on their own perceptions of their performance. Because of the poor resolution, lack of peripheral cues, and lack of depth perception, the pilots found it very difficult to accurately judge where they actually touched down longitudinally. Consequently, their real-time assessment of their performance tended to be more optimistic than the post-run analyses, though the general trends were the same. Still, the transition results are considerably clouded by the degraded visual environment.

While the visual cues were the primary problem in the transition task, crosswinds and turbulence did have an affect on task performance and pilot

ratings. Their effects were felt in higher workload and increased error from the touchdown aimpoint. Longitudinal error was affected by the degraded visual cues, turbulence, and crosswinds, in that order of importance. Lateral error was affected primarily by the crosswinds. Figure 9 shows the Cooper-Harper ratings assigned as a function of turbulence. Performance was judged primarily on control of touchdown accuracy and attitude.

With no crosswind and no turbulence, the pilots felt they were able to consistently achieve desired performance. They reported one minor deficiency. When the aircraft entered ground effect there was a slight tendency to float. The pilots felt that they had to push through ground effect. Pilot ratings were borderline Level 1/Level 2, ranging from Cooper-Harper 2 to 4.

FIGURE 9: Transition Task CH Ratings

With the introduction of crosswinds, the pilots discovered another problem with the visual scene. In crosswinds the HUD-drawn MOS did not line up precisely with the visual runway. It was not so much a difference in displacement as a difference in heading. This discrepancy between HUD MOS and visual MOS was worse with increasing crosswind, and was also usually worse with a crosswind from the right. This problem was a result of free-play and hysteresis in the hardware driving the terrain board camera. Actually, it is probably realistic to expect that in the real aircraft the HUD MOS and the actual MOS will not line up precisely, but in the real aircraft, the pilots would have a much clearer view of the actual MOS in the VFR conditions simulated. In this simulation, where the visual cues were degraded, the pilots depended more on the HUD MOS than they ordinarily would have, and discrepancies between this and the visual MOS made the transition task more difficult.

With w-gust rms = 2 ft/sec or lower, the pilots felt they could consistently achieve desired performance. The turbulence increased workload primarily in control of pitch attitude. Cooper-Harper ratings were borderline Level 1/Level 2, ranging from 2 to 4, with a general trend toward higher ratings with higher crosswinds.

Between w-gust rms = 2.12 and 2.83 ft/sec, the pilots felt they could consistently achieve adequate performance and sometimes desired performance. Cooper-Harper ratings ranged from 3 to 5, mostly Level 2. With crosswinds below 20 knots, ratings were borderline Level 1/Level 2. With crosswinds above 20 knots, ratings were mainly Level 2.

At w-gust rms = 3.54 ft/sec, the pilots felt that they usually achieved adequate performance. Cooper-Harper ratings ranged from 4 to 7, almost all Level 2. They only flew in 25 and 30 knot crosswinds with this turbulence level and there was no significant difference in ratings between these crosswinds.

At w-gust rms = 4.24 ft/sec, the pilots frequently could not achieve adequate performance and there was the first hint of controllability problems. Cooper-Harper ratings were borderline Level 2/Level 3, ranging from 6 to 8. This turbulence level was only used with 30 knot crosswinds.

Post-run analysis showed similar trends, though somewhat lower frequency of desired and adequate performance than the pilots perceived. Analysis showed a definite trend for larger longitudinal error with increasing turbulence. Turbulence did not seem to significantly impact lateral miss distance.

Crosswinds caused increased workload in course control in three ways. First, because of the need to recognize and cancel drift rates due to the crosswinds. Second, because of the mismatch between the HUD MOS and the visual MOS. Third, at the 25 and 30 knot crosswinds the HUD velocity vector would frequently limit against the edge of the HUD, making the steering cues invalid. The pilots were forced to "cage" the velocity vector in order to get good steering guidance. This constrained the velocity vector to the center of the HUD and displayed a "ghost" velocity vector depicting the aircraft's actual flight path. The problem with "caging" the velocity vector was that the pilot could no longer watch the steering commands and the actual runway simultaneously, but had to crosscheck from the center of the HUD to the edge of the HUD. Though there was a general trend toward increased lateral miss distance with increasing crosswind, lateral miss distance was usually within desired criteria. Consequently, though the pilots did mention crosswind as a factor affecting workload, turbulence was a more significant factor.

ROLLOUT SUB-TASK

Figure 10 shows the Cooper-Harper ratings assigned for different crosswinds on dry runways. Figure 11 shows the Cooper-Harper ratings assigned for different crosswinds on icy runways. Cooper-Harper ratings were determined entirely on control of attitude and heading during the rollout, and not stopping distance. Since braking was accomplished by the autobrakes and thrust reversing, both of which were set by the pilots and then usually left alone, stopping distance was not a suitable factor for assigning a Cooper-Harper rating. However, rollout distances were recorded as part of the overall evaluation.

FIGURE 10: Dry Runway Rollout Task CH Ratings

FIGURE 11: Icy Runway Rollout Task CH Ratings

With no crosswind, the rollout was no problem, with the runway icy or dry. The pilots achieved desired performance most of the time and no deficiencies were noted. The pilots rated it solid Level 1, all Cooper-Harper 2's. Stopping distance did depend on runway condition. On the dry runway the average stopping distance was 1270 feet, well within the required stopping distance of 1500 feet. On the icy runway, however, average stopping distance was 1915 feet, over the 1500 foot limit.

With crosswinds the pilots encountered some handling qualities problems. The nature of the difficulties depended on the runway condition.

On a dry runway there were three problems. First was a strong roll transient right at touchdown. This roll was apparently caused by the reaction of whichever gear struck the runway first. Since a crosswind approach is usually made with the upwind wing low, it was typically the upwind gear that hit first and thus the roll was almost always away from the wind. This made the roll tendency even worse since the crosswind then increased the rolling tendency. The higher the crosswind the greater the rolling tendency. The second problem

was a tendency for the aircraft to run in the direction the nose was pointing at touchdown instead of skidding in the direction of the flight path and the nose coming around. The third problem was a tendency for the aircraft to roll over when the pilot abruptly applied an upwind full steering command at a time when the upwind main gear was unstroked at low speeds (below 50 knots). The pilots found these problems to be extremely unusual and felt that they were probably not realistic. McAir suspects that in this region the validity of the tire friction coefficients at large skid angles is questionable, and F-15 experience indicates that, at worse, a skid should have developed.

With a 15 knot crosswind, the touchdown transient and the initial direction change were not difficult to control. The pilots usually were able to counter the direction change at touchdown and keep the airplane within desired criteria (within 12.5 feet of centerline). The task was rated a Cooper-Harper 3. With the 20 and 25 knot crosswinds, the pilots had more difficulty controlling the initial transients. The initial direction change sometimes carried them outside of the desired criteria before they could counter it. The higher the wind, the more frequently they failed to contain the direction change within desired criteria. However, once desired criteria was achieved it was easily maintained. Pilots rated these cases borderline Level 1/Level 2. Ratings for the 20 knot crosswind cases ranged from 3 to 5, mostly Level 2. Ratings for the 25 knot case ranged from 3 to 6, mostly Level 2. With a 30 knot crosswind the pilots were rarely able to contain the initial transient to desired criteria. However, once desired criteria was achieved it was easily maintained. Cooper-Harper ratings were solid Level 2, ranging from 4 to 6. In all cases, the Level 2 ratings were due entirely to difficulties keeping the initial transient within desired criteria. Once recovered from the initial transient, control of heading was no problem. Rollout distance was well within the required 1500 feet in all cases.

On icy runways, the reduced runway friction allowed the aircraft to skid in the direction of the flight path and also seemed to reduce the magnitude of the gear reaction so the initial touchdown transients were not a problem. However, a bigger problem was a tendency to get into a slide downwind that could not be stopped before the aircraft slid off the MOS. Thrust reversing on the runway gave the aircraft a tendency to yaw away from the relative wind during the rollout. The pilot would put in rudder to correct this and the nose would come around, but the aircraft would continue to slide downwind. The slide could not be stopped until the velocity got slow enough to get effective nose wheel steering, but by then the aircraft usually had slid off the MOS. The pilots discovered a technique to counter this slide. When the aircraft started to yaw, the pilot would get out of thrust reverser, the aircraft would then weathervane normally back into the relative wind, and the pilot would then go back into thrust reverser. The pilot might have to go in and out of reverser a few times during the rollout until the nose wheel steering became effective. This technique allowed the pilot to track the MOS

centerline at the expense of increased rollout distance.

With a 15 knot crosswind, the yawing and sliding tendency could be controlled well enough with direct side force control that the pilots didn't need to come out of reverser to keep the airplane within desired criteria. The ratings for these cases were Level 1, Cooper-Harper 2's and 3's. In the 20 knot crosswind cases the pilots noticed the sliding tendency more but were still able to control it without coming out of reverser. The pilots rated this borderline Level 1/Level 2 with Cooper-Harper ratings from 2 to 4, mostly Level 1. In the 25 knot crosswinds the pilots could not stop the slide before getting out of desired criteria. If they came out of reverser, the aircraft was controlled before sliding off of the MOS. If they did not come out of reverser, the aircraft could not consistently stay on the MOS. When the pilots used the technique of coming out of reverser, rollout task ratings were borderline Level 1/Level 2, 3's and 4's, mostly 4's. When they did not come out of reverser pilot ratings were Level 2, 5's and 6's. With a 30 knot crosswind, they had to come out of reverser to stay on the MOS. Pilot ratings were Level 2, 6's and 7's.

In summary, at crosswinds below 20 knots the pilots could maintain desired performance without resorting to coming out of reverser. With crosswinds above 20 knots coming out of reverser became necessary. The aircraft was never able to stop in the required 1500 feet on the icy runway.

FAILURE AND DEGRADED MODES DURING SLAND LANDINGS

Table 2 identifies the 17 failures evaluated during final approach landings. The evaluations were conducted in the SLAND IFPC mode. The table includes a brief description of the effect of each failure and the advisory given to the pilot. Note that all hardover control surface failures gave no advisory to the pilot. The testing was conducted in 15, 20, 25 and 30 knot crosswinds with corresponding turbulence levels. Failures typically occurred about 200 feet AGL which is considered a critical workload transition period for the pilot. The failure/control mode matrix was evaluated randomly during the normal final approach landing evaluations. When a failure was detected, the pilot had a choice to either abort for a go-around or continue his approach and landing to the dry 50 x 1500 foot MOS.

The hardover stabilator failure was the most serious failure evaluated. Three pilots evaluated this failure with a loss of control 50% of the time. However, this failure in the baseline F-15 causes loss of control almost 100% of the time. When the S/MTD aircraft was controllable, pilot comments indicated level 3 handling qualities due to large right or left roll forces depending on which stabilator was hardover. To maintain control of the aircraft, an airspeed below approximately 160 knots was required. The loss of aircraft occurred due to pilot tendency to add power when a failure was detected. One pilot chose to retract the flaps. Flap retraction resulted in reduced stick and rudder forces required to keep the aircraft in 1-g level flight.

The hardover canard failure resulted in roll and yaw transients, but this failure was controllable with full rudder trim. In all cases evaluated, the pilot aborted the landing and felt confident in his control during the go-around to execute a safe landing.

The hardover Nose Wheel Steering (NWS) failure resulted in yaw excursions during rollout. In all case evaluated, the pilot had problems in keeping the aircraft on the MOS (width boundary) during rollout. If the pilot detected the failure and selected castor mode, the effects of the failure were milder due to increase pilot authority.

The dual air data failure caused minor transients. However, this failure caused the IFPC to revert to the conventional mode. Since the pilot was already on his approach speed at the time of the failure, the reversion to conventional mode resulted in a decrease in airspeed which required immediate pilot attention. Pilot selection of emergency air data gains resulted in no transients and provided a safe go-around.

The hardover AOA probe failure with one probe malfunctioning to read a minimum value of -7.5 degrees caused a pitch up transient which was easily corrected by the pilot for a safe landing abort. However, in the case where one probe malfunctioned to read a maximum value of 33 degrees a slow pitch down transient was experienced. In cases evaluated where the pitch down occurred on final approach close to the ground, immediate pilot attention was required. The pilot was able to control the aircraft for a safe landing abort and go-around.

The remaining control surface failures in Table 2 were evaluated with very minor transients which were easily controlled by the pilot. Single engine, afterburner blowout, single hydraulic and dual channel flight control system failures all validated the S/MTD's graceful degradation qualities and maintained controllability.

Overall the pilots were very pleased with the S/MTD's failure/control mode characteristics during final approach landings. Pilot confidence in failure mode procedures were successfully demonstrated.

SUMMARY AND CONCLUSIONS

The objectives to validate the SLAND control laws and failure mode characteristics were successfully completed. Five Air Force test pilots and one NASA test pilot participated in the Air Force Series V+ testing. This effort was a successful milestone in the developmental phase of the S/MTD Simulation Test Program. Air Force pilot acceptance and confidence in the overall S/MTD system design and performance was achieved for flight demonstration. Operational Flight Program control laws were validated prior to Hardware-in-the-Loop verification tests at McAir.

TABLE 2: Failure /Control Matrix

FAILURE	DESCRIPTION	ADVISORY SYSTEM
STABILATOR HARDOVER	15 DEG TRAILING EDGE DOWN (TEU) AT MAXIMUM RATE	NO WARNING
CANARD HARDOVER	35 DEG TRAILING EDGE UP (TEU) AT MAXIMUM RATE	NO WARNING
AILERON HARDOVER	20 DEG DOWN AT MAXIMUM RATE	NO WARNING
RUDDER HARDOVER	30 DEG RIGHT AT MAXIMUM RATE	NO WARNING
RUDDER DAMPED TRAIL	POSITION DRIVEN BY AIR LOADS	MASTER CAUTION LIGHT/TONE/ DISPLAY/CAUTION PANEL
ENGINE NOZZLE	NOZZLE TRANSITIONS TO FAILED OPEN CONTROL LAWS TRANSITION TO CONVENTIONAL MODE	MASTER CAUTION LIGHT/TONE/ DISPLAY/CAUTION PANEL
UT-1 HYDRAULIC SYSTEM	LT/RT FLAPS, AILERONS TO 1/2 POWER, NWS TO DAMPED TRAIL, NOZZLE, BRAKES, AUTOBRAKE, SPEEDBRAKE FAILED	MASTER CAUTION LIGHT/TONE/ DISPLAY/CAUTION PANEL
PC-1 HYDRAULIC SYS	LT/RT CANARDS, STABILATOR TO 1/2 POWER	MASTER CAUTION LIGHT/TONE/ DISPLAY/CAUTION PANEL
ENGINE	UT, PC SINGLE HYDRAULIC FAILED, LT/RT AILERONS, FLAPS, CANARDS, AND STABS TO 1/2 POWER, SINGLE RUDDER COMPLETE HYDRAULIC FAILURE	MASTER CAUTION LIGHT/TONE/ DISPLAY/CAUTION PANEL
DEEC UART	SINGLE AFTERBURNER BLOWOUT, NOZZLE TO FIXED AREA	MASTER CAUTION LIGHT/TONE/ DISPLAY/CAUTION PANEL
DUAL AIR DATA SENSOR	AIR DATA GAINS FROZEN AT LAST VALUE	MASTER CAUTION LIGHT/TONE/ DISPLAY
ATTITUDE DATA	INS AND AHRS DATA LOST	CAUTION LIGHT/TONE/DISPLAY
WEIGHT ON WHEELS	FCS ASSUMES AIRCRAFT IS ON THE GROUND AT ALL TIMES	NO WARNING
AOA HARDOVER PROBE	HIGH - DRIVES TO 33 DEGREES LOW - DRIVES TO -7.5 DEGREES	NO WARNING
IFPC CHANNELS 1 AND 2	LT INLET RAMP MOVES TO EMERG. POSITION, AUTOBRK DISENGAGES, NWS DEGRADED	MASTER CAUTION LIGHT/TONE/ DISPLAY/CAUTION PANEL
IFPC CHANNELS 1 AND 3	LT/RT INLET RAMP MOVE TO EMERGENCY POSITION, AUTOBRAKE DISENGAGES	MASTER CAUTION LIGHT/TONE/ DISPLAY BLANKED/CAUTION PANEL
IFPC CHANNELS 1 AND 4	LT INLET RAMP MOVES TO EMERGENCY POSITION, LEFT NOZZLE FAILED, LT AILERON, FLAP, AND RUDDER FAILED TO DAMPED TRAIL, AUTOBRAKE DISENGAGES, NWS DEGRADED, NOW FAILED TO TRUE	MASTER CAUTION LIGHT/TONE/ DISPLAY/CAUTION PANEL

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