An Aerial Vehicle Enhancement for Mars Exploration

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Abstract - Aerial vehicles have been considered for exploration of Mars for nearly 60 years. Mars is currently the subject of extensive robotic investigations, on the ground, and from orbit. Mars airplanes can provide an intermediate, gap-filling and complementary instrumentation platform. Deployment of a Mars airplane is made difficult by the fact that it must unfold immediately after it emerges from its atmospheric entry aeroshell. While unfolding, the airplane also performs a stressful high speed vertical dive and pullout to generate airspeed. This method consumes a large amount of altitude. An alternate deployment scheme which stabilizes the airplane and reduces the amount of stress applied and altitude lost is a highly desirable technological enhancement. Flight termination using a controlled, survivalable landing can provide additional mission-extending enhancements. A successful demonstration of a Mars airplane technology, utilizing an attitude control system to manage a highly stalled aircraft, and reduce mission risk is reported.

I. INTRODUCTION

A. *The Case for Mars Airplanes*

Mars is currently the subject of extensive robotic investigations. As Mars science makes new discoveries, an increasing number of investigation targets become available. Regional coverage, not possible with a rover, coupled with close instrumentation proximity, not possible with an orbiter, is offered by a Mars airplane. Mars airplanes can provide an intermediate, gap-filling and complementary instrumentation platform. Aerial vehicles offer a unique perspective from which to access and conduct exploration of Mars — or any world with a sensible atmosphere.

B. *Early Mars Airplane Development*

The earliest proposal to use airplanes to access Mar, with human crews, was made by Wehrner von Braun between 1948 and 1952 [1], as illustrated in fig. 1. His proposed design reflected the little that was known about Mars with certainty at that time; it

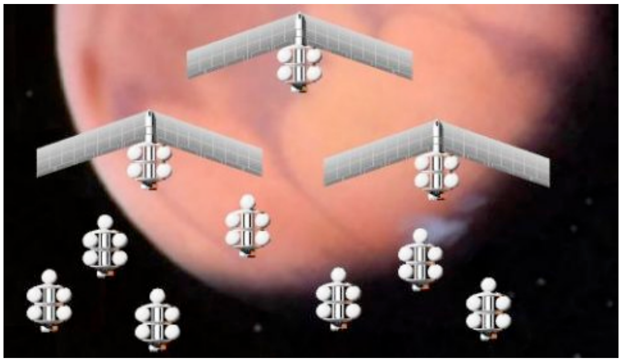

Figure 1 – *Early von Braun concept for human Mars explorations using spacecraft and airplanes*

had a very thin atmosphere and seasonal polar caps. As a result, his Mars airplane design had very high aspect ratio wings, low wing loading, and skis with which to land on the polar snow pack.

Mars airplanes were also studied by the Jet Propulsion Laboratory (JPL), in 1978 as a follow-on to the Mars Viking mission [2]. The thin atmosphere of Mars required special considerations. The resulting design featured high aspect wings in order to minimize airspeed. These wings were to be folded and stowed in an aeroshell and then deployed in mid-atmosphere, in a complex operation. Subsequent studies, tests, and mission proposals by NASA Ames Research Center (ARC) began where the JPL study left off. Model testing was conducted by ARC using NASA 721 and 722, shown in Figs. 2 and 3, to support several Mars airplane proposals [3] [4] [5]. Packaging and mission suitability were given high priority within

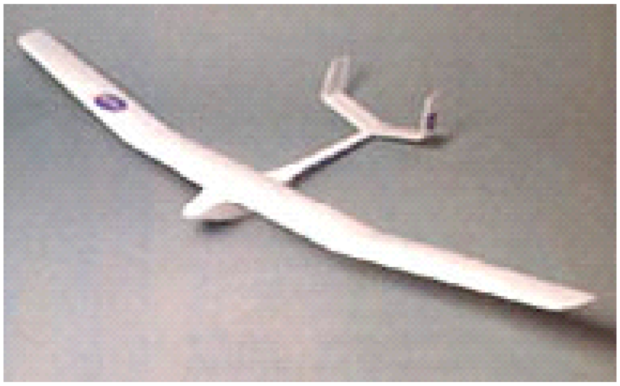

Figure 2– *NASA 721 allowed direct study of low Reynolds number flight*

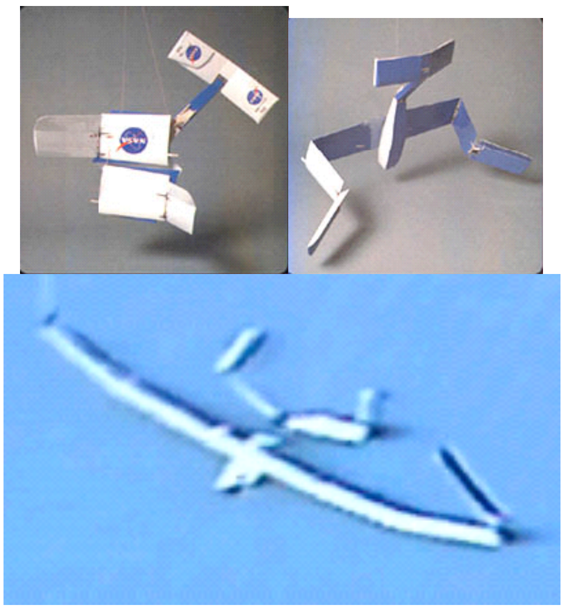

Figure 3 – *NASA 722 was a work horse and provided multiple opportunities to explore deployment techniques.*

the analysis space. ARC has developed Mars airplanes for nearly twelve years, [6] [7] [8] culminating with the technological advance now reported.

II. PROBLEM STATEMENT

A. Deployment

Any Mars probe which enters the atmosphere must be folded and packaged in an aeroshell. For an airplane which must immediately begin flying to survive, a challenging deployment problem is presented. While the airplane is unfolding, it is also diving at a high rate in order to gain airspeed. Finally, a high stress pullout must be performed after considerable loss of altitude. A method of mitigating the high stress and altitude loss during a Mars airplane deployment is highly desirable.

Previous High Altitude Flight Tests (HAFTs), using helium tow balloons, initially conducted by ARC, as shown in fig. 4, and later by Langley Research Center (LaRC) demonstrated the feasibility of Mars flight and the ability to unfold wings. For these tests, the high speed dive approach

Figure 4 – *NASA 731, Orville, Flying on the Edge of Space*

was used. Altitude loss and imposed g-load from a dive is shown in figs. 5 and 6.

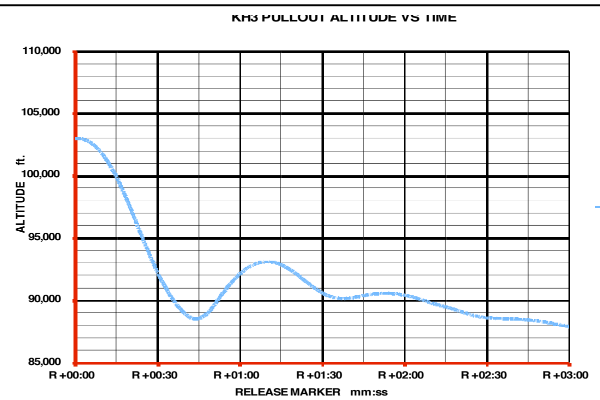

Figure 5 – *Dive deployment consumes altitude*

B. Fight Termination

The endurance of a Mars airplane is limited to approximately one hour. During a typical flight, more data can be acquired than can be down-linked to Earth. Flight profiles in early mission concepts included a mission-terminating surface impact. An alternate landing scheme which preserves more of

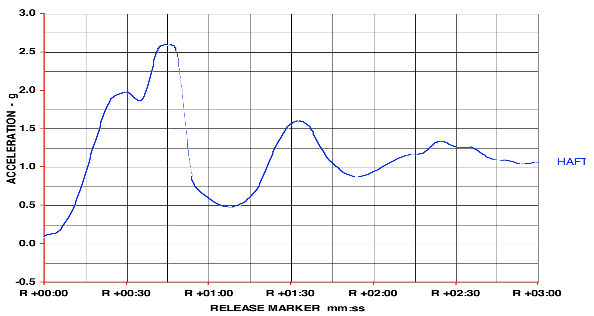

Figure 6 – *Dive deployment is a stressesful first manuever for a Mars aircraft –(peak speed I sM 0.79)*

the data is also highly desirable. In addition, a survivable landing allows the possibility of an extended surface mission.

III. TECHNOLOGY SOLUTION

A. Deployment and Landing

The Mars Advanced Technology Airplane for Deployment, Operations, and Recovery (MATADOR) was designed to demonstrate an enhancement that increases the utility of Mars aerial vehicles. MATADOR uses an attitude control system (ACS) to maintain stability about the three rotational axes. By controlling the attitude, the airplane's rocket powered acceleration has a large horizontal component and a pullout maneuver is avoided. The same ACS is used to initiate a deep stall maneuver to shed airspeed and maintain stability during a soft landing using a vertical thruster.

B. Direction of Technology Enhancement

The MATADOR aircraft design, shown in fig. 7, has been optimized to support the specific test objectives. MATADOR was developed and proposed for testing under the Mars Technology Program, within the Aerial Mobility topic area. The project was based upon the lessons learned from earlier Kitty Hawk 3 flight test activity which utilized a more convential aircraft design (fig 4).

The top level goals and objectives for the MATADOR project are to enhance the utility of Mars airplanes by:

1. Reducing the deployment risk
2. Increasing the amount of data that can be returned to Earth and ensuring its survivability
3. Provide a capability of surviving a landing such that extended surface interactions can occur.
4. Validating the use of analytical tools for predicting Mars airplane performance at low speeds and extreme angles of attack (90 deg at initiation)

Achievement of these goals will provide an enhanced exploration platform for Mars exploration.

IV. TECHNOLOGY DEVLOPMENT

The direction chosen for the MATADOR aircraft was to design an airframe shape that is amenable to control in a highly stalled, low speed condition, then adapt an Attitude Control System (ACS). The pitch attitude of the aircraft is held close to the horizontal by the ACS. Coupling between the pitch, yaw, and roll rotational axes is also counteracted by the control algorithms. The aircraft uses a rocket engine, rather than gravity, to obtain flight speed. The same ACS is then used to stall the aircraft again in order to allow a vertical rocket engine to control the aircraft descent and perform a survivable landing. The plan form chosen was a delta-shape blended fuselage with deployable wingtip extensions at the base, as shown in figs. 7 and 8. The MATADOR technique is illustrated in fig. 9, showing the simultaneous action of the ACS and the forward thrusting main rocket engine.

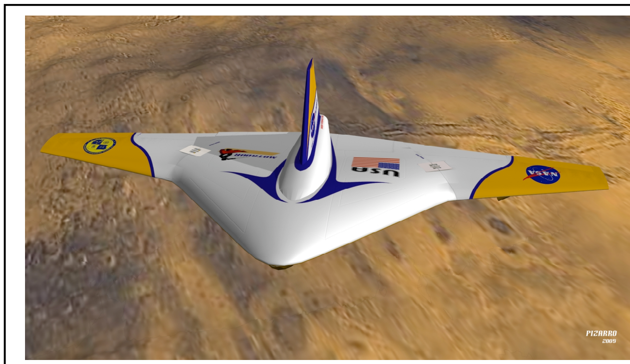

Figure 7 – *MATADOR sweeps across Mars*

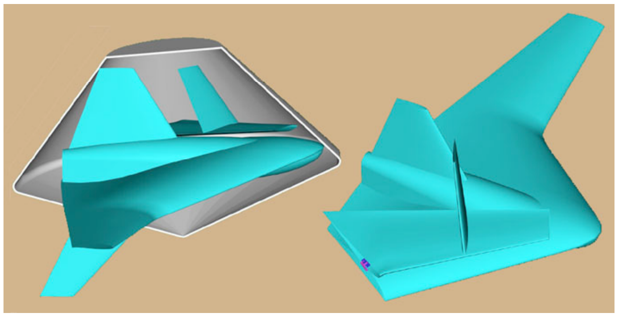

Figure 8 – *MATADOR mating to aersoshell - an efficient packaging scheme is essential*

Figure 9 – *MATADOR provides a robust and safe deployment and landing capability*

A. Test Details

The ACS used for the MATADOR has heritage from an experimental Naval Countermeasures program developed by the Naval Research Laboratory (NRL). This selection significantly reduced development risk and schedule.

The original test plan called for the use of HAFTs to demonstrate MATADOR deployment. Earth altitudes of over 30 km provide an environment that is relevant to Mars flight. Free gliding flight, although necessary to recover the test article, was not a critical part of the test with respect to data acquisition. Considerable test planning, model build-up and pre-test evaluation is required for a free flying model.

Due to a shortfall in expected funding, a major project decision was made to utilize a Vertical Wind Tunnel (VWT) located at Wright Paterson Air Force Base (WPAFB) to focus on the most critical portion of the demonstration: attitude control in highly stalled, low speed, conditions. Speed at low altitude was adjusted to match the expected dynamic pressures (q).

B. Computational Support

As a key part of the technology development, an extensive Computational Fluid Dynamic (CFD) analysis, using a CART3D model, was performed in order to predict performance. A Prandtl-Glauert compressibility correction [9] was applied to the CART3D computational results. The wind tunnel test results that were obtained validate the CFD analysis. This validation now provides a tool that allows definitive Mars airplane designs and testing, as defined by the MATADOR technology demonstration goals.

C. Test Integration

The MATADOR test article was integrated into the VWT by suspending it from above, through its center of gravity (C.G.). as shown in fig. 10. Initial shakedown runs indicated an artifact condition that caused the model to translate laterally in an accelerating dynamic response. This motion will not be relevant in a free flight situation, therefore it was eliminated by adding a vertical restraint below the C.G., also shown. The restraint eliminated lateral motion. while keeping all rotational degrees of freedom free.

All primary testing was performed at vertical wind speeds of 6.1 or 7.6 m/sec. The model was initially positioned in a horizontal position and then released for control by the ACS. Cold gas (N_2) thrusters in the nose and lower body, fired under computer control in order to go to and hold a series of pre-programmed attitudes. Intentional, external disturbances were also introduced and successfully nulled out in some runs as shown in fig. 10. Experimental adjustment of the gains and dead bands constituted the data sweep.

Deployment of the wings from a folded to unfolded condition was not performed since this event would normally be a transient, occurring at high forward speeds. Once the aircraft achieves ~

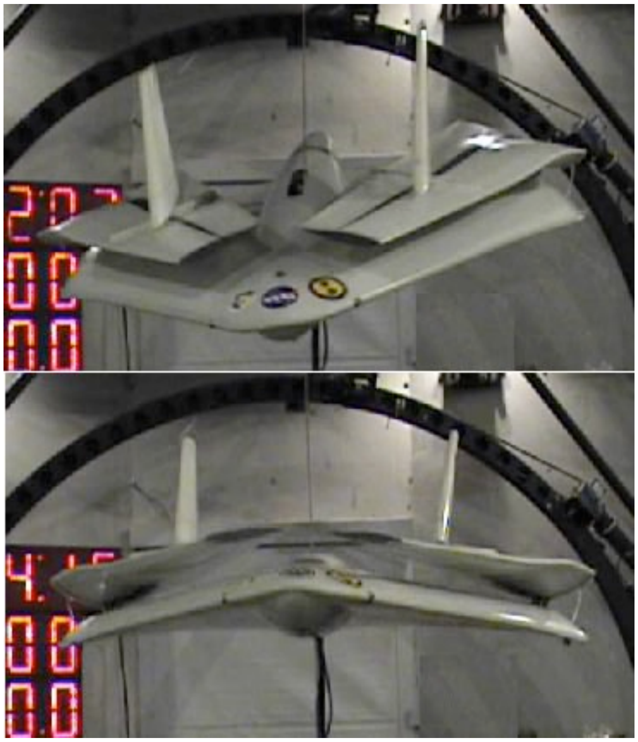

Figure 10 – *MATADOR VWT Testing -disturbedt attittude (above), recovered attitude (below)*

70% of forward speed, the ACS control authority diminishes and attitude is dependant on conventional aerodynamics . High speed wing deployment, as been demonstrated by the Naval Research Laboratory (NRL) [10].

D. Test Results

The VWT experiment was successful in demonstrating the MATADOR technology and proved to be beneficial as a necessary intermediate step before a HAFT is performed. The opportunity to adjust control parameters and repeat test runs is not available in a balloon drop. Misaligned parameters that might adversely compromise a free flight do not threaten a captive wind tunnel model.

1. Qualitative results

The MATADOR aircraft was repeatedly tested in the VWT and demonstrated an ability to hold commanded attitudes. This was true even when external upsets were applied to the aircraft manually, as illustrated in fig. 10. The overall tracking performance of MATADOR was satisfactory

Additional tuning of the aircraft control scheme, with the possible upgrading of thruster components, will be required prior to a HAFT. Sufficient data was obtained to confidently make such changes.

2. Quantitative Test Data

The performance of MATADOR has been characterized analytically by NRL [11]. Figs. 11, 12, and 13 were taken from an arbitrary gain set, as most of the sets produced similar results for tracking capability and stability maintenance. Unless otherwise noted, all data is taken at 6.1 m/sec vertical wind speed. Roll tracking was not tightly bounded, but did not diverge at any point after the lower cable was added. The amplitude of the roll angle grew as pitch dipped below 0 deg as

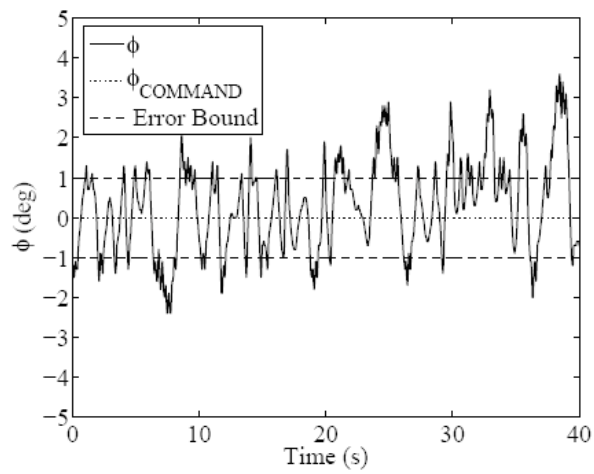

Figure 11 – *Roll tracking*

seen in fig. 11.

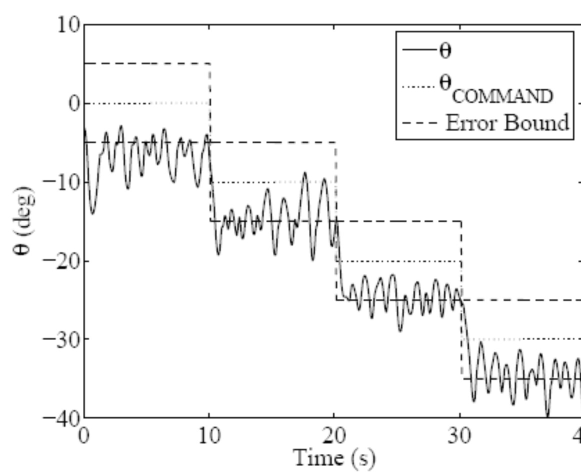

Figure 12 – *Pitch tracking*

Fig. 12 shows that pitch tracking was satisfactory and the response oscillated about the lower, more easily achievable, error bound.

The yaw response remained fairly consistent throughout the pitch angle sweep (fig. 13). The pattern was disrupted somewhat below $\theta = -10$ deg. The model exhibited a natural swaying tendency that was most likely a result of stored energy in the tether. The yaw dead band had to be relaxed in order to deal with a divergent mode that appeared initially. This phenomenon subsided once the dead

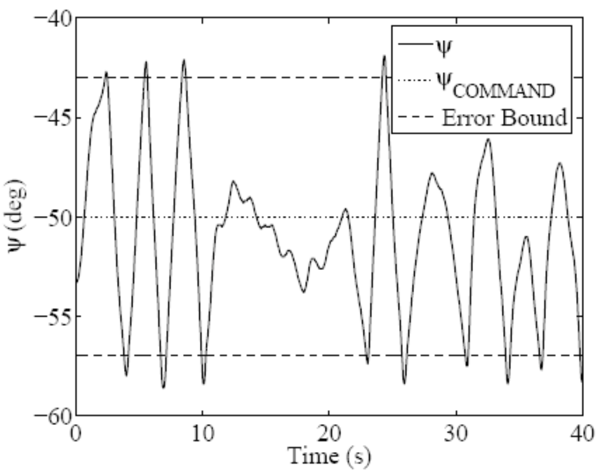

Figure 13 – *Yaw tracking*

band was increased to 7 deg.

Fig. 14 shows the pitch tracking performance at an airspeed of 7.6 m/sec. The aircraft is able to maintain a pitch angle of -15 deg, but is unable to bring the nose up to the lower bound of -5 deg for the next command. This demonstrates an excellent

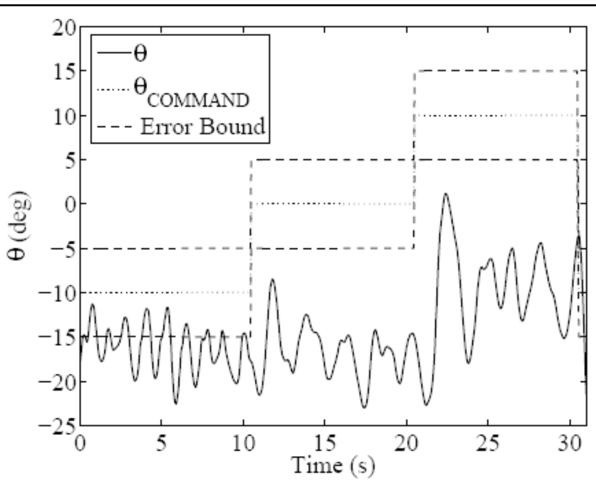

Figure 14 – *Pitch Tracking – 7.5 m/sec*

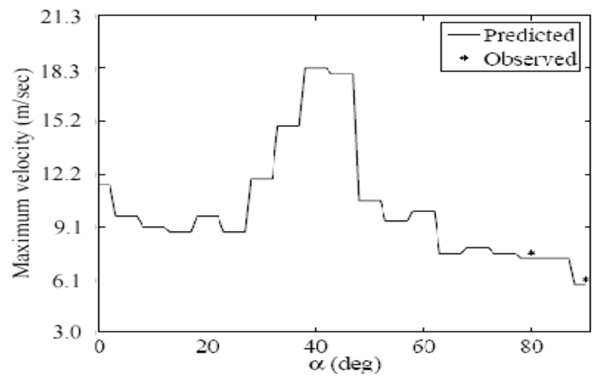

Figure 15 – *Conversion Corridor – Wings Closed*

correlation with the conversion corridor (fig. 15) that was predicted by the aerodynamic model, with the aircraft losing controllability in the predicted region, validating the CFD performance predictions

Figs. 16, 17, and 18 show a portion of the test in which the disturbance rejection capabilities of the control system were tested. The model was perturbed with a stick during a regulated 10 deg nose down position. The tick marks along the command line are the points of perturbation. Note that there was some lag due to the operator in the loop recording of these events and that all events may have not been marked.

The direction and magnitude of the disturbance inputs were arbitrary, so only a general perception of the performance is available. An estimate about the direction of the input can be made based on the

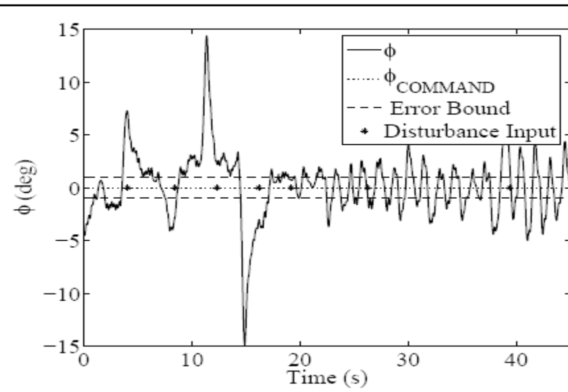

Figure 16– *Roll Disturbance Rejection*

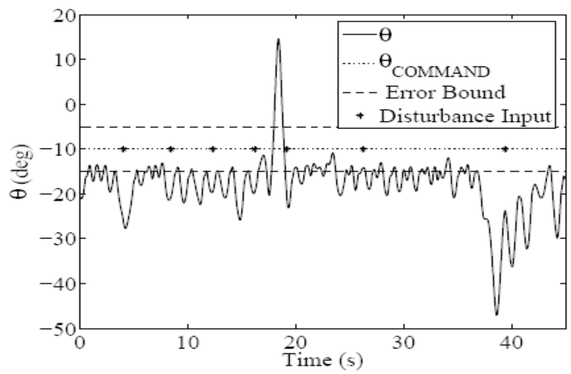

Figure 17 – *Pitch Disturbance Rejection*

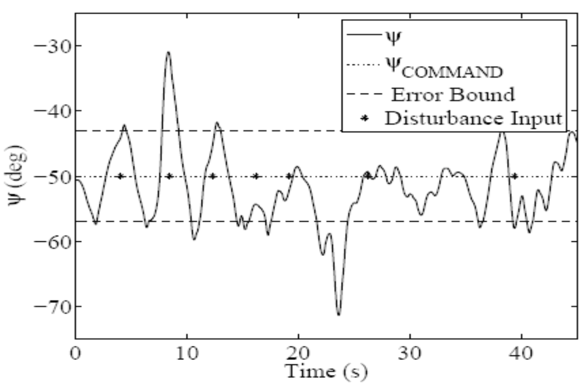

Figure 18– *Yaw Disturbance Rejection*

aircraft's response although some coupling will be present for any given instance. The control system was able to attenuate the effects of the external inputs. Inputs of 10 deg or more were given to all three axes, with all demonstrating reasonable responses. Note the greater struggle encountered by the aircraft as it brings its nose up from a downward deflection as opposed to a recovery from a nose up input.

Tab. 1 summarizes the disturbance rejection results. Due to the arbitrary and coupled nature of the inputs, conventional control response metrics are not available. Instead, a measurement of time was taken from the peak of the disturbance to the next crossing of the error bound.

Axis	Disturbance Magnitude (deg)	Rise Time (sec)
Roll	13.3	2.2
Pitch	+19.1	0.4
Pitch	-31.5	4.7
Yaw	11.9	0.9

Table 1 – Disturbance Rejection

V. CONCLUSIONS

The state of Mars airplane technology has been enhanced. An effective means of controlling the deployment and landing of a Mars airplane through attitude control in highly stalled, low speed conditions has been demonstrated. Sufficient data necessary to plan additional aggressive terrestrial tests and predict performance of actual Mars airplanes has been obtained. CFD analyses have been validated by wind tunnel testing. These analyses, can now be extended to definitive Mars airplane designs, an important technology demonstration goal. Mars exploration missions can now be planned in which the inherent benefits of an airplane can be used to advantage while overcoming previous shortcomings.

ACKNOWLEDGMENT

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