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Possible Deficiencies in Predicting Transonic Aerodynamics on the X-43A

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NESC Position Paper

ITA #: 03-002-E	
Requestor Name: Richard Wood NASA Langley Research Center	Requestor Contact Info: (301)-864-6174 r.m.wood@larc.nasa.gov
Short Title: Possible Deficiencies in Predicting Transonic Aerodynamics on the X-43A	
Description: Monitoring and evaluation of X-43A independent FRR process in its disposition of the issues raised in a dissenting opinion e-mail (officially documented in HyperX RFA 20).	
Date Received: 10-28-03	Date ITA/I Initiated: 11-06-03
NESC Chief Engineer (NCE) Assigned: Michael Gilbert	NCE Contact Info: (757) 864-2839
Lead Assigned: Steven G. Labbe	Lead Contact Info: (281) 483-4656
Date ITA/I Concluded: March 18, 2004	

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John Ruppert, Flight Control Systems, JSC

Assessment / Evaluation Approach

NESC involvement was initiated by a dissenting opinion e-mail from Mr. Rick Wood (NASA LaRC – AAAC) received on October 28, 2003. The dissenting opinion raised three potential overarching aerodynamic issues. 1) Incomplete aerodynamic analysis of Flight 1 (a failure to quantify all contributing factors); 2) The need to develop and/or validate scaling laws for ground test to flight databases supporting Flight 2; and 3) The need to correct known errors & deficiencies in ground based experimental & computational data sets.

The NESC Director negotiated with the X-43A Return-to-Flight (RTF) Manager, Luat Nguyen (NASA LaRC – Space Access & Exploration Program Office), to have these issues addressed through the existing independent X-43A Flight Readiness Review (FRR) process with NESC monitoring and evaluation. This independent technical forum was staffed with the appropriate aerodynamic expertise to address the issues raised. If necessary, the NESC would be available for a second look into how the X43A FRR board dispositions the issues. Steve Labbe, acting NESC Discipline Expert for Flight Sciences, was assigned as lead for this evaluation.

The dissenting opinion originator documented his issues and concerns in Request For Action (RFA) 20, included here as Reference 2, to officially initiate the X-43A FRR Committee process.

Risk Assessment

The initial X-43A flight test, June 2, 2001, resulted in a mishap and loss of the vehicle. A mishap investigation board (MIB) report and findings, including the established root cause, were publicly released on July, 23, 2003. *The X-43A Flight 1 Hyper-X Launch Vehicle (HXLV) failed because the vehicle control system design was deficient for the trajectory flown due to inaccurate analytical models (Pegasus heritage and HXLV specific), which overestimated the (control) system margin – X-43A Mishap Investigation Report, Vol. I.* – included as Reference 1. Several specific errors were noted, 1) HXLV aerodynamics – failure to model changes to wing, fin and rudder airfoil shapes due to addition of thermal protection system (TPS); 2) Fin actuation system (FAS) modeling – under prediction of the control surface hinge moments and FAS compliance; and 3) Parametric uncertainties – insufficient variation in the aerodynamic, FAS and control system models. In response to the MIB findings, the X-43A program has been working RTF through an approved Corrective Action Plan (CAP) over the last two years.

The aerodynamic issues raised in the dissenting opinion address the program's risk mitigation approach to encountering a roll disturbance during the boost phase. It was the initiators technical opinion that the 2nd flight of the X-43A has a minimal chance for success due to un-modeled and/or mis-modeled aerodynamic phenomena in the transonic through supersonic Mach number range. There is good likelihood that the vehicle will experience un-commanded rolling moments (roll disturbance) in the transonic flight regime. Failure to manage the resulting disturbance magnitude could lead to loss of vehicle. This mission success hazard (covered under X-43 Hazard Report (HR) No. 2602: Loss of Control: HXLV during boost) was classified by the program's Risk Management Board with a Severity of Category II – Loss of HXRV and a Probability of D – Unlikely but Possible to Occur. Given the loss of vehicle during the boost phase on Flight 1, an independent assessment of the issues raised in the dissenting opinion was warranted. The X-43A programs Hazard Action Matrix is shown here, with HR No. 2602 classified.

	PROBABILITY				
HAZARD SEVERITY	A: LIKELY TO OCCUR FREQUENTLY	B: LIKELY TO OCCUR SEVERAL TIMES IN LIFE OF PROGRAM	C: LIKELY TO OCCUR AT SOMETIME DURING PROGRAM	D: UNLIKELY BUT POSSIBLE TO OCCUR	E: EXTREMELY IMPROBABLE
CATEGORY I DEATH					
CATEGORY II LOSS OF HXRV PRIOR TO ENGINE DATA/LOST TIME INJURY				**2602**	
CATEGORY III HXRV DAMAGE-RTB					
CATEGORY IV MISSION ABORT-RTB (Cost or Schedule Impact)					

Data Reviewed

The NESC monitoring and evaluation of FRR assessment process included both face-to-face meetings and teleconferences with the X-43A aerodynamic team, the FRR aerodynamic experts and other aerodynamic consultations. The NESC reviewed in detail, the RFA 20, the program response to RFA 20 (and associated reference material) as well as the FRR assessment for content and applicability. The NESC confirmed that the FRR was addressing each of the issues raised in RFA 20. The NESC did not conduct a root cause analysis or an independent analysis of the RFA 20 issues.

X-43A Program Response to RFA 20:

The complete X-43A program response to RFA 20 is provided as Reference 3.
In summary, the X-43A program adopted a philosophy towards risk reduction and mitigation that the program believes is conservative and appropriate for an X-vehicle flight project. Recognizing that the HXLV is not intended to be a production unit, the program weighed the upfront non-recurring costs associated with developmental testing and analysis, against total program budget and risks. In response to the MIB findings and recommendations, the program developed a CAP to support the RTF effort with a number of aerodynamic related elements. All of the aerodynamic testing, analysis, and modeling related actions have been fully addressed, and additional efforts above and beyond those specifically outlined in the CAP have been exercised. These efforts

encompass the RFA 20 issues. The program's response deferred in the conduct of any additional test or analysis in response to RFA 20, but rather addressed each specific issue and provided appropriate references. It is the program's position that the extensive testing and analyses conducted, combined with the design approach of building in large stability and control margins provide a high level of robustness to the issues raised in this RFA. Documentation and references to the following work were provided and reviewed by the FRR aerodynamic experts and the NESC.

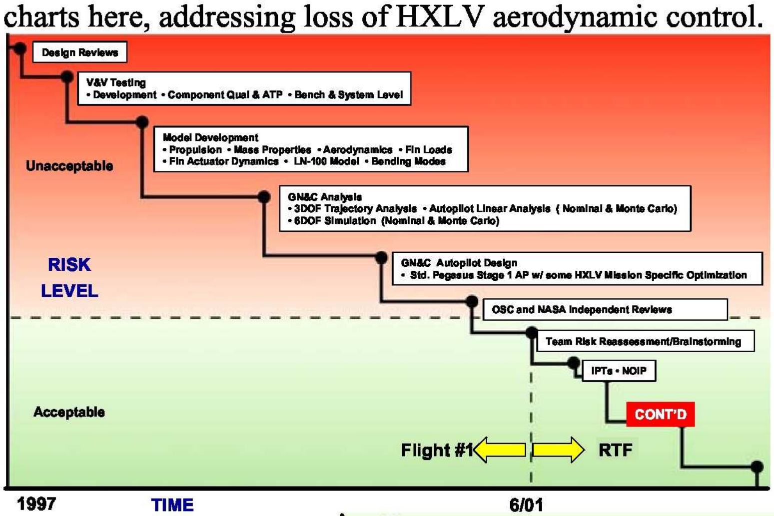
The CAP and additional RTF aerodynamic activities included the following updates:

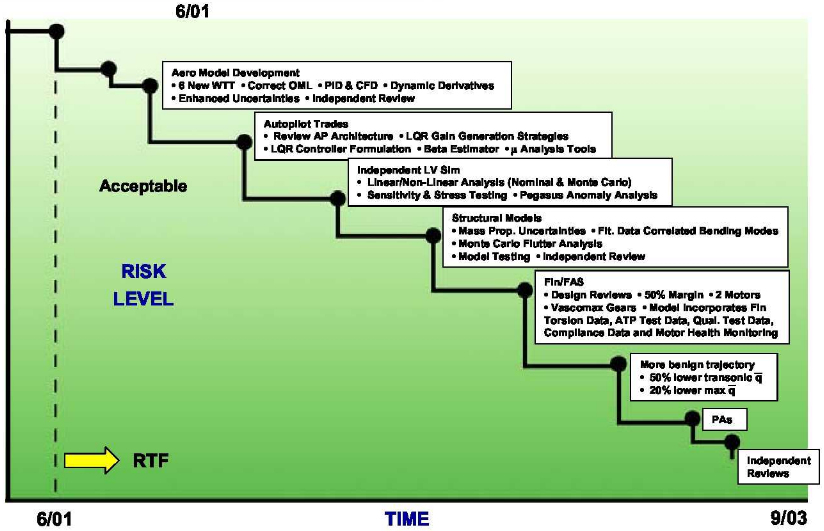
1) Took detailed measurements of the 2nd flight vehicle and developed new wind tunnel model hardware and CFD geometries to match the "as flown" configuration.
2) Conducted an extensive HXLV wind tunnel test program (10 test entries in 7 separate wind tunnel facilities) to completely redevelop the entire set of HXLV aerodynamic data bases, including aerodynamic uncertainty levels. The primary differences between pre and post-flight 1 wind tunnel testing were:
    a. Correct modeling of TPS on the wing and fins.
    b. Accurate wing to fin distance (resulted in 2" longer stack in full-scale).
    c. Both left and right wings instrumented for wing root bending moment.
    d. Addition of 2.5-degree fin deflections (*0,* 2.5, *5.0*).
    e. Added Mach 0.975 to test matrix.
    f. Improved angle of attack and sideslip resolution in test matrix.
    g. New HXLV model fin instrumentation and specific attention to calibrations and data quality
3) Conducted a parallel Computational Fluid Dynamics (CFD) analysis effort.
4) Conducted independent reviews of all aerodynamic data derived from testing and analysis to ensure that the databases utilized for flight simulation and autopilot design are complete and accurate for flight 2.
5) Conducted extensive reviews of the first HXLV flight data and the available Pegasus Launch Vehicle telemetry and identified "disturbances" that could be attributed to aerodynamic related anomalies.
6) Utilized state-of-the art techniques and procedures developed by the joint NASA/DOD Abrupt Wing Stall (AWS) Program experts to examine and appropriately design for potential roll disturbances and dynamics, including unsteady CFD, and simulation models.

Recognizing, however, that the state-of-the-art in transonic high-angle-of-attack unsteady aerodynamics is such that it is not possible to predict these characteristics with a high level of confidence, the project also took the approach of increasing the flight control robustness.

7) Designed the 2nd HXLV for flight control robustness to the possible adverse roll disturbance characteristics by:
    a. Modifying the trajectory to reduce the dynamic pressure (by ~50%) at transonic conditions to reduce aero loads relative to available control capability
    b. Doubling the torque capability of the booster fin actuator to further increase margin
    c. Conducting autopilot trades to identify design options of enhancing transonic flight dynamics robustness
    d. Developing systematic uncertainty models and conducting appropriate Monte Carlo trajectory simulation analysis
    e. Conducting worst case stress cases to define the boundaries of controllability.

These aerodynamic and flight control RTF activities are highlighted in the risk waterfall charts here, addressing loss of HXLV aerodynamic control.





Consequently, the X-43A program strongly believes that the associated risks have been reduced to acceptable levels for Flight 2 and that these efforts encompass each of the issues identified in RFA 20.

FRR Committee's Review of Programs Response to RFA 20:

The X-43A program response formed the basis for the FRR committee's review of RFA 20. The FRR aerodynamic experts spent a considerable amount of time discussing the RFA and the program response. This included a face-to-face meeting at LaRC with the project and the initiator of the RFA as well as numerous FRR meetings, teleconferences and follow up discussions. The NESC monitored this FRR activity. The FRR Committee's final report was provided by letter, Reference 4, to the Airworthiness and Flight Safety Review Board (AFSRB), and includes their complete review, assessment and recommended disposition of the RFA 20 issues.

The FRR condensed RFA 20 and combined it with RFA 17 (Reference 6) into a single overriding issue – the susceptibility of the HXLV to a wing rock/wing drop type of roll disturbance brought on by sudden asymmetric flow separation on the HXLV wing. The project thoroughly addressed roll disturbances in response to RFA 17 by developing a roll disturbance model and conducting Monte Carlo and stress simulation analysis. Four roll disturbance model variations were assessed. The model variations included the disturbance magnitude, onset, frequency content and architecture (single triangle, triple triangle, sinusoidal) as well as the flight condition at which the disturbance is encountered. The largest roll disturbance observed in flight or wind tunnel testing was equivalent to a rolling moment coefficient delta of 0.0043. The models included magnitude variations up to a 0.01075 roll moment delta coefficient level, or 2.5 x 0.0043, in the simulation analyses. The Monte Carlo analysis results indicate that the HXLV flight control system meets all phase and gain margin requirements (Nominal 6dB Gain / 45deg Phase; Dispersed 3dB Gain / 20deg Phase) for all the variations analyzed.

Additionally, when the same dispersed parameter values that result in a very good match of the Flight 1 loss of control are applied in the Flight 2 simulation, the predicted vehicle motions are very benign. Linear analysis indicates that with these parameter values a large stability margin (approx. 6 dB) is provided in flight 2, whereas similar analysis of Flight 1 shows negative stability margin (-2 dB). Finally the "extracted" disturbance models from Flight 1 data and Pegasus flight data were evaluated and flight control system robustness was demonstrated.

Stress case analysis can be used to estimate the expected roll disturbance controllability limit. When combined with a worst case combination of reduced roll damping, reduced aileron effectiveness and other key parameters, the max roll disturbance level assessed can produce loss of control cases. This implies a roll disturbance margin factor of ~2.5, when coupled with the simultaneous occurrence of these other dispersions.

Two members of the FRR aerodynamics team independently estimated the maximum reasonable roll moments generated on the HXLV due to asymmetric flow separation. Assuming flow separation over one entire wing would yield an equivalent rolling moment coefficient delta maximum of 0.01. This maximum value is encompassed by the levels analyzed in the program's roll disturbance assessment. Thus, while the detailed physics of possible flow separation may not be known prior to flight, it is the opinion of the FRR aerodynamics team that the flight control system exhibits robustness to the maximum estimated flow separation disturbance described by the initiator.

In summary, the FRR found that the RFA 20 initiator recommended closure on many sub-issues associated with each of the three overarching technical issues. The FRR determined that the project did respond to each issue, however for the most part, the project response does not specifically accomplish what the initiator was asking. It is the opinion of the FRR committee that in general, the requests were out-of-scope for this project. Furthermore, the FRR found that the project response to this RFA demonstrates a significant effort (wind tunnel and CFD) to understand the vehicle aerodynamics along with a comprehensive Monte-Carlo trajectory analysis to assess the uncertainties. The project recognizes there are aerodynamic uncertainties associated with this configuration flying at high angle-of-attack at transonic conditions. The project has elected to ensure through test and analysis with Monte-Carlo simulation stress testing, that the flight control system is robust to the range of possible aerodynamic uncertainties and roll disturbances predicted for the X-43 vehicle.

As reported to the AFSRB, the FRR aerodynamics team agrees with the project response to RFA 20 and does not recommend any further testing or analysis as requested by the initiator of the RFA.

NESC Monitoring and Evaluation of FRR Process regarding RFA 20:

The NESC believes that the X-43 FRR aerodynamic experts appropriately focused the RFA 20 assessment and has verified that the X-43A FRR process adequately reviewed, investigated and responded to the aerodynamic issues raised. The NESC confirmed the independence, appropriate expertise, thoroughness, disposition and documentation of the X-43A FRR Aerodynamic assessment of the programs response to RFA20. The program provided extensive reference material (Wind Tunnel Test Reports, CFD Analysis Reports, Aero Dynamic Data Base Development including uncertainties, Independent Aero Uncertainty Evaluation, etc.), with its response to RFA 20. The NESC reviewed this material and did not identify any technical issues in the material provided.

Based on the programs reliance on a robust flight control system to mitigate the risks associated with a potential roll disturbance encounter, the NESC requested support from JSC Flight Control expertise (J. Ruppert). At NESC request, additional GN&C system design and verification data was provided by the program. These presentations documenting the GN&C system design and development, the certification process (including multiple independent simulations), as well as the Monte-Carlo simulation results, were reviewed for potential technical issues. No technical issues were identified and appropriate stress testing of the GN&C system via multiple flight simulation results was indicated.

These NESC findings were reported to the AFSRB on February 9, 2004 and the Headquarters Office of Safety and Mission Assurance (OSMA) Integrated Mission Assurance Review (IMAR) on March 11, 2004 and are documented in this report.

Updated Risk Assessment

A potential increased risk level was highlighted by the originator of a dissenting opinion to the NESC. The NESC Director negotiated with the X-43A Program to have this addressed through the existing independent X-43A FRR process with NESC monitoring and evaluation. The FRR process has refuted the dissenting opinions higher level of risk and independently confirmed the programs defined level of risk. As a result RFA 20 was dispositioned with no further action. HR No. 2602, which encompasses the RFA 20 issues, remains classified as (II/D – Loss of Vehicle/Unlikely to Occur). This risk assessment was reported to and concurred with by both the AFSRB and the Office of Safety & Mission Assurance (S&MA) Integrated Mission Assurance Review (IMAR).

Additionally, it should be noted that RFA 20 addresses a matter of mission success on what is characterized as a high risk flight research experiment. Safety of the flight crews, ground personnel and the general public are not impacted by this particular issue and therefore would not be affected by the final outcome.

Findings / Root Cause / Observations

Findings:

The X-43A FRR process has been exercised with monitoring/observation from the NESC.

The NESC has verified that the X-43A FRR process adequately reviewed, investigated and responded to the aerodynamic dissenting opinion (RFA 20)

The X-43A FRR process is sufficiently independent of the program
The X-43A FRR team employed the appropriate technical expertise in their assessment

The X-43 FRR process has assured that the program address the overarching issues raised in RFA 20

The FRR process has refuted the dissenting opinions higher level of risk and independently confirmed the programs defined level of risk. As a result, HR No. 2602 remains classified as (II/D – Loss of Vehicle/Unlikely to Occur).

The FRR and NESC presented the summation of these findings at the AFSRB, February 9, 2004 and at the Headquarters Office of Safety & Mission Assurance (S&MA) IMAR on March 11, 2004.

An AFSRB action to directly report the final disposition of the RFA 20 issues to Mr. Wood was subsequently completed by both the FRR committee and the NESC ITA/I lead.

Recommendation

The NESC has determined that no further action is required.

APPENDICES

References

1. Report of Findings - X-43A Mishap, Vol. I. by the X-43A Mishap Investigation Board, May 08, 2003
2. Hyper-X Flight Readiness Review (FRR) Request For Action (RFA) 20 – X-43A 2nd Flight Technical Issues Memo Dated October 31, 2003, Richard M. Wood
3. X-43A Response to RFA 20, Rev. A, X-43A RTF Program Manager, January 15, 2004,
4. Flight Readiness Review of X-43A, Letter to the Chair, Airworthiness and Flight Safety Review Board (AFSRB) from the Chair, X-43A Dryden Flight Readiness Review (FRR) Committee, February 04, 2004.
5. Response to X-43A RFA 20 Analysis Evaluation titled "Attachment #2", Richard M. Wood, January 27, 2004
6. Hyper-X FRR RFA 17 – Assessment of Potential Adverse Aileron Effectiveness, Dan Murri

Minority Report (dissenting opinions)

No dissenting opinions within the NESC.

It should be noted that the dissenting opinion initiator maintains his initial position. He has documented these continuing concerns (Reference 5) to the FRR committee, the NESC and the LaRC Director.

X-43A Dissenting Opinion NESC Evaluation Lessons Learned

The following lessons learned address both the general nature of this evaluation and subsequent response to the dissenting opinion as well as the X-43A FRR Process and its application to a wider range of NASA programs.

The X-43A Flight Readiness Review (FRR) process defined in Dryden Handbook DHB-X-001, Airworthiness and Flight Safety Review, Independent Review, Mission Success Review, Technical Brief and Mini-Tech Brief Guidelines, appears to be an excellent FRR process that

- Provides an alternative approach to the more traditional single meeting method
- Avoids the potential for the large data dump and "rubber stamp" type review
- Allows for FRR initiated actions, necessary response time and appropriate follow up on the identified technical issues.

- Provides a mechanism for dissenting opinions via Request For Action (RFA)
- Is independently established from outside the program
- Can draw on the necessary expertise and skills from across the agency as required
- Reports independently to the Airworthiness and Flight Safety Review Board (AFSRB) on a programs flight readiness

Potential issues related to the process are

- Extensive interfacing between the independent review committee and the program can potentially lead to a situation wherein the FRR members become advocates and fail to maintain their critical thinking and independence although oversight from the Center Chief Engineer helps prevent this form occurring.
- Reliance of the project on the FRR committee for advice on how to meet the requirements of the ARSFB

  Note: The Center Chief Engineer, who commissions the FRR with inputs from the S&MA director, chairs the AFSRB and provides independent oversight to prevent either situation. In either case, it is the FRR that presents a report and briefing to the AFSRB which is comprised of senior management. This provides yet another check on the independence between the project and the FRR committee

A possible alternative is that the FRR could be comprised of two components. A continuous beginning to end group to maintain continuity and a rotation of specific experts to provide "new blood" and ensure a critical review aspect is maintained.

The NESC as well as the agency needs a strategy for addressing dissenting opinions. Several issues must be considered including,

- It is in NASA's best interest to create an environment that encourages dissenting opinions within its programs
- Policy on the appropriateness for referring to existing independent authority.
  Note: The NESC wants to encourage programs to use existing independent technical forums – With the NESC available for a 2nd look only as required.
- The necessary monitoring and follow up requirements on referred items
- Potential for large resource commitment working phantom issues.
  Note: If misdirected can distract limited program resources from other more critical areas of concern.

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	NESC Director	Date

Version	Description of Revision	Author	Effective Date
Final	X-43A Dissenting Opinion Evaluation Final Report – Position Paper	Steven G. Labbe	03-18-04

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