2010

Development of a hover test bed

Jason Alan Williams

DEVELOPMENT OF A HOVER TEST BED

by

JASON ALAN WILLIAMS

A THESIS

Submitted in partial fulfillment for the requirements
for the degree of Master of Science in Engineering
in
The Department of Mechanical and Aerospace Engineering
to
The School of Graduate Studies
of
The University of Alabama in Huntsville

HUNTSVILLE, ALABAMA

2010

In presenting this thesis in partial fulfillment of the requirements for a master's degree from The University of Alabama in Huntsville, I agree that the Library of this University shall make it freely available for inspection. I further agree that permission for extensive copying for scholarly purposes may be granted by my advisor or, in his/her absence, by the Chair of the Department or the Dean of the School of Graduate Studies. It is also understood that due recognition shall be given to me and to The University of Alabama in Huntsville in any scholarly use which may be made of any material in this thesis.

(student signature) 29 April 2010 (date)

THESIS APPROVAL FORM

Submitted by Jason Alan Williams in partial fulfillment of the requirements for the degree of Master of Science in Engineering with an option in Aerospace Engineering and accepted on behalf of the Faculty of the School of Graduate Studies by the thesis committee.

We, the undersigned members of the Graduate Faculty of the University of Alabama in Huntsville, certify that we have advised and/or supervised the candidate on the work described in this thesis. We further certify that we have reviewed the thesis manuscript and approve it in partial fulfillment of the requirements for the degree of Master of Science in Engineering with an option in Aerospace Engineering.

4/29/2010 ____________________ Committee Chair
(Date)

4/29/10 ____________________

4-29-10 ____________________

____

5/1/10 ____________________ Department Chair

____________________ College Dean

8/4/10 ____________________ Graduate Dean

ABSTRACT
The School of Graduate Studies
The University of Alabama in Huntsville

Degree Master of Science in Engineering
College/Department Engineering/Mechanical and Aerospace Engineering

Name of Candidate Jason Alan Williams
Title Development of a Hover Test Bed

This research examines the development, validation, and verification of a hover test bed at the Missile Defense Agency's National Hover Test Facility located at the Air Force Research Laboratory on Edwards Air Force Base, California. This work's scope includes the development of a test bed for exoatmospheric kill vehicle testing in an integrated hover test arrangement. The approach involved reactivation of the facility, design of a risk reduction methodology, and vehicle performance verification. Details from a combustion stability issue on the divert engine is investigated, and changing the diameter of the injector reduced a first tangential combustion chamber mode combustion instability from 17.8% to 0.8%.

Abstract Approval: Committee Chair Robert A. Frederick Jr.

Department Chair [signature]

Graduate Dean Debra M. Moriarity

ACKNOWLEDGMENTS

First, I would like to thank God for giving me the privilege and ability to work on such an exciting project. I especially would like to thank my parents, Eddie and Cynthia Williams, for their patience, encouragement, and support throughout my entire life. In addition, I would like to thank the Missile Defense Agency and in particular, Mr. Richard Matlock, for giving me the opportunity to lead this development effort on such an important program as the Multiple Kill Vehicle program. Moreover, if not for the great professionalism, teamwork, expertise, and dedication of the integrated government and industry team, the Agency would not have such a successful testing milestone. I would like to particularly like to thank Mr. Eddie Kern, Mr. Ryan George, Mr. Brian McKee, Mr. Randy Riley, and the entire crew at the National Hover Test Facility. Finally, I would like to thank Dr. Robert Frederick for his patience and allowing me the needed time to complete this thesis while working for the government in parallel.

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

ACS	=	Attitude Control System
ASAT	=	Antisatellite Weapon
CG/MOI	=	Center of Gravity / Moment of Inertia
CSCI	=	Computer Software Configuration Item
DACS	=	Divert and Attitude Control System
DCS	=	Divert Control System
EKV	=	Exoatmospheric Kill Vehicle
GSE	=	Ground Support Equipment
HTB	=	Hover Test Bed
HTS	=	Hover Termination System
HTV	=	Hover Test Vehicle
HWIL	=	Hardware-in-the-Loop
IMU	=	Inertial Measurement Unit
KHIT	=	Kinetic Kill Vehicle Hardware Integrated Test
LEAP	=	Lightweight Exoatmospheric Projectile
MDA	=	Missile Defense Agency
MDPAL	=	Mobile Decontamination and Particulate Analysis Laboratory
MKV	=	Multiple Kill Vehicle
NHTF	=	National Hover Test Facility
RF	=	Radio Frequency
STE	=	Special Test Equipment
UAH	=	University of Alabama in Huntsville
UDS	=	Universal Documentation System
Wi-Fi	=	Wireless Fidelity

CHAPTER 1

Introduction

According to the National Missile Defense Act of 1999, it is the policy of the United States to deploy as soon as is technologically possible an effective National Missile Defense system capable of defending the territory of the United States against limited ballistic missile attack (whether accidental, unauthorized, or deliberate) with funding subject to the annual authorization of appropriations and the annual appropriation of funds for National Missile Defense.[1] To execute this policy, the Department of Defense chartered the Missile Defense Agency to develop and field an integrated, layered, Ballistic Missile Defense System to defend the United States, its deployed forces, allies, and friends against all ranges of enemy ballistic missiles in all phases of flight as shown below in Figure 1.1.[1]

Figure 1.1 – The Ballistic Missile Defense System[1]

This figure shows the three phases of flight: boost/ascent, midcourse, and terminal. In addition, the figure gives a depiction of the weapon systems either under development or currently deployed to the services to intercept a threat in its flight trajectory.

1.1 Multiple Kill Vehicle

The Missile Defense Agency (MDA) chartered a project to develop, test and deploy the Multiple Kill Vehicle (MKV) payload. In this particular effort, MDA utilized the Hover Test Bed (HTB) to verify propulsion subsystems for the MKV program. MDA tasked this program office with developing and testing the next generation of exoatmospheric kill vehicles used to intercept and destroy intercontinental ballistic missile threats launched against the United States or our Allies. To verify the vehicle propulsion system operates as designed, the program contracted Lockheed Martin Space

Systems Company in Sunnyvale, California, and charged them with developing and testing this system.[2]

The Lockheed Martin MKV concept, shown in Figure 1.2, consists of a carrier vehicle with a bandolier of smaller kill vehicles that deploy in the midcourse phase of flight to intercept identified threat objects.

Figure 1.2 – Notional Multiple Kill Vehicle Payload[3]

To test this concept, the program office static hot fire tested the carrier vehicle propulsion system in August 2007 verifying propulsion subsystem performance, and subsequently hover tested the prototype concept in December 2008 verifying integrated vehicle operation. This thesis presents facility capabilities, test article risk reduction testing, and verification of the test bed through a free flight hover test of a Lockheed Martin multiple kill vehicle concept.

CHAPTER 2

Literature Review

Hover testing is not a novel approach to the testing portfolio. The origin of hover testing goes back to the first free flight Antisatellite Weapon kill vehicle hover test in 1979 of a spinning solid propulsion system.[4] The next series of testing occurred from 1985-1987 when the government awarded four technology development contracts tasking propulsion developers TRW, Aerojet, Rocketdyne, and Bell Textron to develop miniaturized exoatmospheric kill vehicles.[4] The Air Force wanted to assess the integration and testing risk of these advanced technologies in an observable testing environment.[4] Therefore, the Air Force conducted a trade study examining possible options for this type of testing including indoor/outdoor testing, air-bearing/air-table, howitzer targets, vacuum chamber hover, and tether/tower drop tests. This trade study completed in 1987 and the Air Force selected hover testing in a free flight, indoor, controlled environment.[4] The Air Force Research Laboratory selected the Test Area 1-125 at Edwards Air Force Base for the testing facility.[4]

Recoverable ground testing has many payoffs such as minimizing the risk and expense of full up space flight tests. In addition, it delivers an exclusive method to verify target track jitter, pointing and inertial measurement accuracy, and vibration during dynamic conditions, center of gravity control, thruster misalignment, and total vehicle integration interaction as a risk reduction technique.[4] Through this testing, programs caught critical systematic issues such as loss of track, control anomalies, and hardware and electronics integration issues early on because the vehicle was available for inspection after test.[4] Major programs have taken advantage of this type of risk reduction testing such as the Kinetic Kill Vehicle Hardware Integrated Test (KHIT), Lightweight Exoatmospheric Projectile (LEAP), Antisatellite Weapon (ASAT), Exoatmospheric Kill Vehicle (EKV), and most recently, MKV.[4]

To expand on the risk reduction benefits, hover testing reduces risk by obtaining recoverable flight data used to anchor models and simulations, predict space flight performance, assess multiple thruster firing interactions in a dynamic environment, kill vehicle structure, seeker field of view, Inertial Measurement Unit (IMU) disturbances, and control system authority.[4] Moreover, hover testing collects pre- and post-flight vehicle center of gravity measurements, delivers truth data for in flight kill vehicle center of gravity and moment of inertia migration and thruster misalignment analyses.[4] In addition, hover testing allows Divert and Attitude Control System (DACS) observation because it obtains free flight data for comparisons with component and static tests, delivers visual verification of possible DACS operation anomalies not observable during space flight, and allows test article recovery for post-test divert thrust vector alignment measurement verification.[4] Finally, from the test execution side, it allows for crew training in test article handling, ground support equipment operations, and range operations, and reduces risk on flight procedures and methods by dry running them in a relevant environment. Table 2.1 summarizes leveraging hover testing as risk reduction to flight-testing.

Table 2.1 - Risk Reduction Benefits to Flight Testing[4]

Flight Test Phase	Flight Operation where Risk is Reduced
Integration/Checkout	• Avionics/Propulsion Integration • System Checkout Procedures
Pre-flight	• Seeker Tests • Propulsion System Pressurization • Flight Software Load • Flight Software Standby Mode • Telemetry • IMU Bias • Power Enable • Projectile Propulsion Enable • Attitude Reference
Flight/Intercept	• Umbilical Disconnect • IMU and Seeker Data Processing • ACS and Divert Operation • Telemetry Data Processing • Telemetry Data Transmission
Ground Support Equipment	• Vehicle Handling • Data Handling

As mentioned previously, many programs benefited over the years from risk reduction hover testing. KHIT was the pathfinder test series conducted from July 1988 to April 1989.[4] KHIT was part of the flight experiment DACS technology development and contained a cruciform divert system with a bowtie configuration Attitude Control System (ACS), heavyweight thrusters with identical flight response characteristics, on-board IMU, and with telemetry transmitted to the ground.[4] However, KHIT used no sensor in this initial test series.[4] Next, the KHIT program conducted a free flight test series from November to April 1989.[4] The first three attempts ended in testing anomalies where the program office applied lessons learned to ensure a fourth test, a successful hover test.[4] The KHIT static and hover test series proved many lessons learned. These lessons included the capability to repeat hover tests within days of each other, the vehicle must account for adequate engine seal protection, intensive combined system tests are needed prior to the test event, pin game the loading operations, center of gravity and moment of inertia operations were susceptible to facility internal air currents, and the team must maintain configuration control of the experiment.[4]

The next program to hover test in August and September 1989 was the Onboard Navigation, Transition, and Real-time Guidance Experiment Test program.[4] This program successfully verified the vehicle guidance system via a closed looped autopilot, found a hard body in presence of a target plume, and demonstrated target track during the DACS firing.[4] Lessons learned from this experiment included discipline in following procedures, cross training, miscommunication between test team members, calibration of equipment, and crew training timelines.[4]

The next program to hover test was the Advanced Hover Interceptor Technology program from July 1990 to January 1991 where the first test executed a stable hover and tracked a satellite in orbit via a mirror.[4] The second hover test of the series had a failure of the burst disk prior to flight.[4] This failure caused the program office of another major defense program, ASAT, to program in hover testing for the ASAT prior to flight-testing.[4] Lessons learned included increased quality assurance practices from pressurant hardware failure due to vendor contamination.[4]

Next was the Boeing LEAP hover test series from August 1991 to January 1992.[4] The first hover test in the series had trouble tracking the target and with navigation drift.[4] The team identified the observable issue and corrected the errors for the second hover test.[4] Lessons learned from this key series included challenging hardware and software integration, restrictive cryostat gas supply requirements, inadequate divert valve actuation pressure margin, include IMU and accelerometer calibration data in combined system tests, perform longer pre-flight accelerometer bias, and lock range to minimize navigation drift, and the standalone capability of ground test support equipment minimizes setup and integration at the facility.[4]

Next to hover was the System Concept and Integration Technology program in April of 1992. [4] This test validated propulsion and the guidance, navigation and control system of the vehicle.[4] However, target track was lost during divert engine firing and it tracked the plume for the full duration of the flight. [4] Lessons learned were more precise alignment of the divert plane was required, increased control margin, and the increase the fidelity of the ACS.[4]

The next hover test was Rockwell LEAP test in August 1992. [4] This test validated the vehicle system integration and performance, high vehicle stability and correlated center of gravity and moment of inertia migration simulations. [4] Lessons learned from this test included seeker gas supply contamination issues and a propulsion issue with the commanded versus actual divert pulses; and led to the successful LEAP #3 flight test.[4]

The next major test at the facility was the August 1992 Rockwell Advanced Kill Vehicle static test that uncovered valve switching problems and verified the fix using follow on Hardware-in-the-Loop (HWIL) testing.[4] Upon fixing the problem realized in the static test and verified in through HWIL, the January 1993 range safety stopped the hover test of this vehicle due a valve switching issue. [4] The team recovered the hardware for testing, identified a timing problem, and verified the issue on a follow on ground test at the facility.[4] A guidance, navigation, and control command and valve driver incompatibility caused an uncontrollable roll that could not be detected in HWIL, air bearing, or static testing.[4] The main lesson learned here was HWIL testing can miss system interaction problems such as the timing problems and programs need alternative testing methods, like hover testing.[4]

As activity at the facility continued, the first solid propellant system to hover was next in line. The Boeing solid LEAP vehicle conducted its static test in February 1993.[4] However, weld process issues, telemetry dropouts, hydrochloric acid condensation causing obscuration, and luminescent plume from the exhaust gas caused a secondary combustion reaction during this key risk reduction test.[4] Taking these lessons learned from the static test, the hover test of this unit followed in April 1993 with successful target acquisition and track with line of sight dither.[4]

The following major hover test was the Army's Kinetic Energy ASAT hover test in August 1997.[4] This test demonstrated integrated vehicle performance under propulsive free flight conditions with high accuracy pointing during several zero gravity free fall maneuvers.[4] Several lessons learned came out of this testing including higher fidelity modeling needed to characterize the lag between engine commands and full thrust, the use of slightly off-nominal launch attitude in pre-flight modeling and simulation adds robustness, and the stack-up of hardware misalignments and accurate structural stiffness is crucial.[4]

Finally, the last hover test prior to the MKV test was of the EKV in November 1998.[4] This test validated: all models prior to space flight, closed loop hover flight control, pointing error performance, assessed interaction between propulsion, structure, seeker line of sight, IMU, and tracker and control system, and characterized pre- and post-test thruster vector misalignment. [4] The major lessons learned included fit checks need to be required prior to test operation, plan for a wet Center of Gravity / Moment of Inertia (CG/MOI) measurement in case the vehicle configuration changes near testing, and ensure proper manufacturing quality assurance.[4]

There were several other notable hover and static tests over the years, but the same theme prevails: industry greatly benefits from this type of ground testing prior to flight-testing. Therefore, all major deployable systems of the ballistic missile defense system were static and hover tested at the National Hover Test Facility prior to flight-testing. Therefore, it was both logical and desirable that the MKV, investigated in this program, take these same steps as risk reduction to the overall payload system.

MDA re-activated the National Hover Test Facility (NHTF) in 2006 to begin testing of its third generation of kill vehicles. MDA intended to incrementally static fire and hover test this new generation of future kill vehicles focusing on flight representative hardware and software of increasing complexity. However, hover testing is not the penultimate test for qualifying a kill vehicle for space flight. Instead, it is an integral part of the full complement of ground testing that, in its totality, verifies as many requirements as possible before flight-testing. Without hover testing, programs transfer much higher risk to flight-testing and defer the verification of key requirements to those high priced, highly visible, flight tests. While hover testing requires a unique software build and a modest allocation of program resources, it has proven repeatedly to be cost effective by identifying critical integration, software, and procedural issues.[5]

CHAPTER 3

Approach

3.1 Test Article Development

To verify the upgraded facility capability and to increase the technology development readiness of the MKV program, a project was created to design, develop, and test a MKV concept. The test article is shown below in Figure 3.1.

Figure 3.1 – Hover Test Article[3]

The test article consists of a forward avionics subassembly containing the sensor and forward processing unit; eight kill vehicle envelope simulators and four kill vehicle mass simulators; an aft avionics subassembly for power and instrumentation; and a propulsion subassembly containing four divert thrusters, four attitude control thrusters, and four pressurant tanks.[6] Table 3.1 outlines the key parameters of the test article.

Table 3.1 - Key Vehicle Parameters[3]

PARAMETER	SI	ENGLISH
Diameter	844 mm	33.2 in
Length	1,640 mm	64.6 in
Mass	211.3 kg	464.9 lbm
Kill Vehicles	12	12

This test was a free flight, closed loop, hover test conducted at NHTF. The prime developer, Lockheed Martin, went through a formal system engineering development cycle to deliver the test article to the facility for testing. The test article development was broken up into seven main areas: systems engineering; software; avionics; structures; propulsion; Special Test Equipment (STE); and Ground Support Equipment (GSE).[6] The author of this paper presided over, approved all of the development processes, and maintained the ultimate design authority granting final approval to all designs and tests.

The team utilized a rigorous and structured systems engineering process in the development of the hover test vehicle. The process consisted of a flow decomposing the overall kill chain functions into vehicle level functions. These functions were allocated to the vehicle hardware components and requirements were derived from this requirements set. The vehicle design was then conducted followed by design verification, integration, and finally the test itself. This is a classical systems engineering process used throughout industry and academia. The functional allocation of the vehicle was broken out into several subsections: operations, communications, maintenance, range safety, acquisition and tracking, and guidance, navigation and control.[6] To ensure traceability of requirements the team used a specification tree and requirements flow. A rigorous verification plan was used and tracked in an electronic database to ensure each requirement and specification was verified prior to testing.[6]

Moreover, key technical performance metrics were developed to track progress and margins throughout the design and integration phases of the program. These metrics included key measurements like wet mass and pointing vector control.[6] The overall vehicle was broken up into subsystems handled by subject matter experts. These subsystems were avionics, propulsion, kill vehicle simulators, software, and structures. [6] All interfaces for these subsystems were defined and controlled for these subsystems using a classic N-squared diagram as shown below in Figure 3.2.

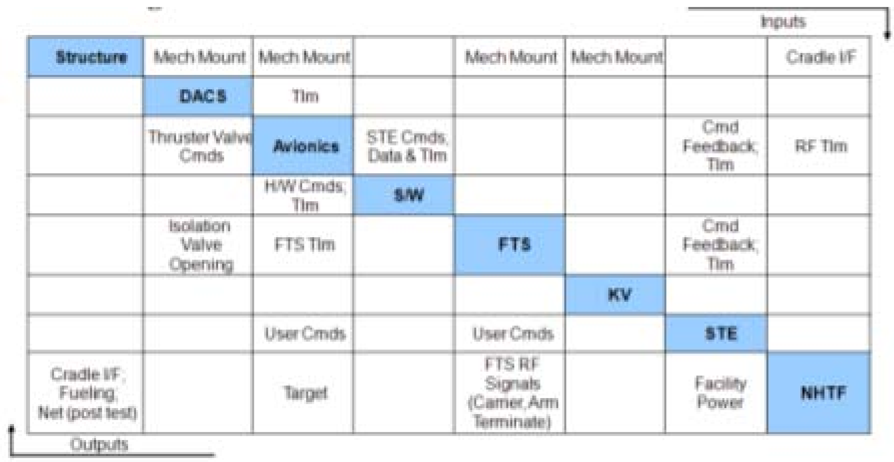

Figure 3.2 – Test N-Squared Diagram[6]

This diagram also included non-vehicle related interfaces such as the test facility and special test equipment. Finally, a rigorous risk assessment and mitigation plan was developed and executed during this program. Risks were identified by the respective subject matter experts and closed by reducing risk through a risk waterfall approach managed by the systems engineering team.[6]

The software portion of the vehicle was developed using an open architecture model based approach by Octant Technologies. The software was required to execute the flight profile, conduct all guidance, navigation and control, acquire the target, track the target, continue the profile if loss of track using the on-board IMU, maintain the vehicle within the flight safety envelope, and deliver health and status to the STE. [6] A rigorous build process was used in the flight software builds. A clear four part build software development and verification process was used in the development path. Testing of the software was done at three distinct levels: individual software unit testing, unit integration testing, and Computer Software Configuration Item (CSCI) qualification testing. [6] Individual software unit testing ensures correctness of algorithms and logic employed by each software unit and that the unit satisfies its requirements and minimizes functional and integration errors of the software unit, and checks functionality and performance in models and in hand-code. [6] Unit integration testing is testing of two or more integrated software units to minimize functional and integration errors of CSCI. [6] All newly developed or modified software undergoes unit integration testing. CSCI qualification testing verifies that the software meets the requirements specified in CSCI Software Requirement Specifications document and is performed on avionics engineering development unit hardware, including all software image processing robustness analyses.[6] To test the guidance, navigation and control algorithms, the team ran Monte Carlo runs in a processor-in-the-loop environment. Prior to each build release, specific systems engineering requirements had to be met. Specifically, for Build 3, all functional verification testing had to be complete and for the final build, Build 4, flight performance verification testing had to be completed. [6] All of this verification testing was done in both an open and closed loop environment on actual pathfinder avionics hardware to replicate flight as much as possible.[6]

The avionics system leveraged commercial off the shelf technology where applicable. This included the power-conditioning unit, mission computer, batteries, IMU, telemetry, camera/seeker, band pass filter, instrumentation module, valve drivers, flight safety termination receivers, flight termination and telemetry antennas, and all bulkheads for the forward and aft modules. [6] To ensure the avionics met the rigorous vibrations of the hover environment, a detailed vibrations analysis was conducted on the avionics components. As a result of this analysis, many of the commercial components were reinforced and strengthened to meet the environments. [6] The system was tested at both the forward and aft subsystem level and integrated level to ensure complete mission success. Two of these tests, the breadboard communications risk reduction test and camera characterization test, were both conducted at NHTF to both reduce hardware and range operations risks. [6] The communications test was used to ensure no telemetry was dropped due to interference and Radio Frequency (RF) multi-path influences with the commercial wireless telemetry system, evaluate RF link closure under both stable maneuvers and varying degrees of vehicle instability, assess high bay induced RF multi-path influences using 802.11G signal, assess signal strength from the vehicle in and around the safety region, identify and assess data packet dropouts and the potential causes, and assess antenna locations and types. [6] Moreover, the camera characterization testing exercised the integrated test team and defined the filter, focus, and aperture settings of the camera using a mock target through net obscuration.[6]

All structural modes and frequencies using the mission duty cycle were designed to avoid any possible dynamic amplification of the system and any critical frequency modes of the commercial avionics components. [6] Key loads and stress analyses were conduced based on worst case loading conditions. [6] All component analysis assessments were based on expected worst-case dynamic loads combined with other expected loads to achieve a robust design. [6] In addition, a complete thermal analysis was completed for the exposure of the external components due to plume heating.[6]

The STE included the capability to perform internal self-testing of the hardware components. The STE responsibilities were to display, monitor, and record all mission computer telemetry and random access memory; deliver umbilical power safe to turn on; electrical isolation; Inter-Range Instrumentation Group time processing; liftoff sensing; video/data feeds for remote viewing; enable the forward and aft avionics power supplies; and deliver two discrete signals for the flight termination system.[6] As a lesson learned from the past, grounding of these key components is critical to operation and test mission success. Therefore, all STE grounding was defined and designed well in advance with the proper isolations in place.[6] The GSE was used both in vehicle assembly and in verification testing. All DACS weld fixtures, avionics vibration test fixtures, assembly fixtures, hover testing cradle, and additional fixtures for transportation were designed, built, and under configuration control throughout the process.[6] In addition, the team built both an electrical and mechanical simulator to serve as pathfinders for the hover test vehicle. The electrical simulator was used in all interface checkouts with the GSE and contained a functional avionics suite used in software checkouts.[6] The mechanical simulator was used for interfacing with vehicle GSE and used as a training tool for testing personnel and for proofing of procedures prior to the test event.[6]

3.2 Test Facility Development

As mentioned previously, the National Hover Test Facility is a Missile Defense Agency ground-testing asset operated by the Air Force Research Laboratory at Edwards Air Force Base, California. In addition, before conducting the MKV test it was almost ten years since the previous test occurred. Therefore, MDA chartered the BMDS Kill Vehicles office to bring this facility's capabilities into the twenty-first century. Some capabilities remained, some were updated, and some were new altogether. The author of this paper presided over and approved all of the facility development and engineering functions for the program office at MDA. This included bringing the facility capabilities, processes, procedures, training, and personnel into a streamlined state of the art ground testing system and verifying these capabilities through testing.

3.2.1 NHTF Overview

The NHTF is located at the Air Force Research Laboratory site at Edwards Air Force Base, California and is shown below in Figure 3.3.

Figure 3.3 – The National Hover Test Facility[3]

The NHTF is comprised of an office complex, high bay test area, low bay control room, mechanics shop, instrumentation and clean room annex, Red Crew Response Trailer , Breathing Air Trailer and a Mobile Decontamination and Particulate Analysis Laboratory (MDPAL), plus several other smaller buildings for storage and support.[7] Moreover, the HTB includes the NHTF, operational safety services, personnel, plans, procedures, processes, and supporting equipment. [7] The test bed is defined using open hardware interfaces, open architecture, and model generated flight software that allows for rapid software development, hardware integration, and maximum reuse for subsequent hover tests.[7] To the maximum extent possible, the test bed uses commercial-off-the-shelf electronics and hardware components for compatibility and ease of supply.[7]

The HTB's main purpose is proving the test article's functionality in hover and static testing by closed loop control, imaging of a reference target, and transmitting video and flight data for post-test recording and processing.[7] The crew also conducts hazardous operations with the article including propellant sampling, propellant and pressurant loading, ordnance installation and removal, vehicle recovery, detanking of residual propellants and pressurant, and hardware decontamination.[7] The NHTF equipment ranges from CG/MOI machines, a 50-ton overhead bridge crane, and equipment used for integration, preparation, propellant and pressurant loading and retrieval of the article.[7] HTB personnel perform all hazardous and non-hazardous duties related to the test.

To facilitate a standard documentation process within the HTB Integrated Product Team comprised of all stakeholders, the facility requires all users to submit documentation using the Universal Document System (UDS) format.[7] The UDS delivers a common language and format for stating requirements and for preparing responses. The first of these documents is the Program Introduction Document delivered around 15-18 months prior to the test.[7] This document is the initial planning document that officially introduces a program and establishes the scope and duration of program activity. Next, the test facility delivers a Statement of Capabilities document to the customer around 12-15 months prior to the test date.[7] This document delivers the facility's response to the Program Initiation Document and serves as the basic agreement between the customer and the facility guiding the more detailed planning directives.

Next, the customer delivers the Operations Requirements Document around 9-12 months prior to the test date.[7] This document describes in detail the customer's requirements for a specific test, or series of tests. In response to the Operations Requirements Document, the test facility delivers the Operations Directive Document around 6 months prior to test.[7] This document details all functions, support equipment, and personnel duties for the operations and testing. Other documents of interest include the Air Force Form 813, Request for Environmental Impact Analysis and Air Force Form 27, and the Experimental/Test Operation Safety Permit.[7]

3.2.2 NHTF Facility Systems

The NHTF maintains the capability to store and handle Department of Transportation Class1.3C explosive ordnance, as well as the capability to deliver the fluids and gases listed in Table 3.2.[7]

Table 3.2- Propellant and Pressurant Storage[7]

Specification	Fluids/Gases Name
MIL-PRF-26539E	Propellants, Dinitrogen Tetroxide
MIL-PRF-27404C	Monomethylhydrazine
MIL-PRF-27401D	Gaseous Nitrogen
MIL-PRF-27407B	Gaseous Helium Type 1, Grade A

The facility ensures these propellants and pressurants meet particulate purity specifications in accordance with IEST-STD-CC1246D Level 100.[7] To verify this purity specification, the facility chemically analyzes propellants and gases to certify that they meet the applicable specification/sampling requirements of the user and deliver a copy of the certification to the users. To analyze these samples, the NHTF MDPAL is one of the upgraded capabilities at the HTB. The MDPAL is a 100K class clean room delivering particle counting with the use of a microscope/computer system contained within a

Level 100 flow bench, two wet stations within vent hood (deionized water and isopropyl alcohol) for cleaning contaminated hardware, two vacuum ovens for cleaning contaminated hardware, deionized water production capability, independent supply of gaseous nitrogen, a diesel generator with fuel tank for power in the event of facility power loss, and environmental monitoring and controls.[7]

For test article mobility operations, the High Bay has a bridge crane with remote operation capability to lift 50,000 lbs with the main hook, 10,000 lbs with the auxiliary hook, and 1,000 lbs with a nylon rope winch.[7] In addition, the facility uses a platform scissors lift to raise and lower the Test Article Launch Cradle and Umbilical.[7] The platform, controlled by remote, lowers the Hover Launch Cradle upon liftoff of the Test Article, and is adjustable. The HTB crew places the Hover Launch System such that with the test article present, the centerline of the test article shall encompass the target.[7] The cradle system, in combination with the scissors-jack pallet will align in pitch, yaw, and roll.[7] The Hover Launch Cradle has a secure and adjustable physical interface with the platform for the purposes of securing, raising the cradle to test article launch height, and lowering the cradle.[7]

The weather plays an important role in the loading, unloading, and testing of hypergolic propellant systems due to the health and safety hazards of the fluids. Therefore, wind direction and speed play a critical role in loading operations. The facility has the capabilities available to monitor and record the temperature, relative humidity, barometric pressure, and wind conditions approximately 75 meters from and anywhere inside the High Bay.[7] An unobtrusive, passive wind speed indicator monitors the conditions on the launch platform.[7]

3.2.3 NHTF Test Instrumentation

Since visual evidence is both key to test article operations and possible anomaly investigations, the application and use of video and still cameras is paramount in hover testing. The facility delivers mounting fixtures for additional test video cameras, and delivers still digital and high-speed film coverage as needed for documentation of pre- and post-test activities.[7] All cameras are remote controlled and are exercised prior to launch.[7] Digital still and high-speed film cameras are controlled using a computer-controlled sequencer capable of starting and stopping each individual camera at a pre-determined time relative to either an operator input, or a sequence start signal received from the customer.[7]

Since test article CG/MOI measurements are critical to vehicle stability, the facility has a CG/MOI machine capable of handling vehicles < 500lbs for nominal vehicles and a larger Space Electronics model machine for heavier vehicles >500lbs.[7] Obtaining this information prior to flight is a key baseline reading. In addition, knowing the system is clean of contaminants that could cause harm in test is critical. Therefore, NHTF has a Class 10,000 clean room for non-hazardous component buildup, a Class 100,000 clean room for contaminated hardware handling, and the MDPAL Class 100,000 clean room.[7]

The target location for the facility varies on the particular test in question and the facility can modify these targets to meet customer needs. However, current targets in place are the west target stand locations are located 55 meters and 100 meters from the center of the high bay.[7] The south roll up door, when open, delivers line-of-sight access to the 200 meter and 800 meter target stand locations.[7]

Receiving and storing the test data is also a critical function. Therefore, NHTF delivers the capability to receive downlinked data using RF, Wireless Fidelity (Wi-Fi), and or Fiber Optics.[7] NHTF currently only delivered dish antennas and transmission line from the antennas to the control room, and had no recording capability for data transmitted via Wi-Fi, but worked with the MKV team making this recording option available for the MKV hover test. The NHTF data coordinate system conforms to the Earth Centered, Earth Fixed standard.[7] Digital Data Acquisition and Control System is used for general-purpose facility data and controls.[7] Data acquisition is synched with Inter-Range Instrumentation Group.[7] The existing system has the capability to record instrumentation data for (32) thermocouples, (16) strain gauge transducers (pressure & thrust), and (48) Solenoid valve control interfaces in the High Bay.[7] The Datamax handles 88 differential channels with voltage inputs from 1 to 40 volts amplitude, and displayed in digital volts, sine waves, spectrums, or various other displays.[7]

3.2.4 NHTF Safety

For safety considerations, NHTF requires two methods of vehicle safety. The first of these methods is the 35' x 65' x 25'containment net inside the High Bay.[7] The net is comprised of 3/16" strand, fire retardant, high tenacity nylon with knotted corners.[7] Supporting 5/8" yalon rope is in a cross section of approximately 14" by 14".[7] In the bottom net section, 1/8" galvanized steel cable is in a cross section of approximately 8" by 8" terminated to 3/8" galvanized steel cable that completes the outer boundaries of the net and divides the bottom of the net into three main sections of equal parts.[7] The second method of containment is the Hover Termination System (HTS) used as an added layer of article, personnel, and facility safety.[7] The crew can activate the HTS to end the free flight if the vehicle is observed to be malfunctioning. If ending free flight is not a necessary safety function for the article, then the crew can utilize the HTS for activating ordnance venting any high-pressure gas after the article has come to rest post-flight. [7] This makes the article much safer to handle during vehicle recovery.

One of the specialized aspects separating the facility from others around the country is the ability to handle and load the specialized propellants and pressurants required for testing. NHTF delivers full hypergolic liquid propellant and pressurant loading and detanking services for test articles. [7] NHTF developed processes, procedures and hardware for hydrazine based liquid fuels and liquid oxidizers. [7] A nominal propellant load system is composed of a load cart, vacuum cart, and propellant detank system cart for each propellant. [7] To protect the crew, the loading personnel wear Level-A protective suits. [7] To supply breathing air to the Level-A suits, the facility utilizes a Breathing Air Trailer capable of simultaneously supplying air to four Level-A suits at nine stations strategically placed in the high bay with two regulators and quick disconnects at each one. [7] The system has a built in emergency backup system in the event of primary system failure and rated to supply air to two members in suit for a minimum 30 minutes. [7]

Other testing factors, like electrical static discharge and lightening protection are considerations in a low humidity environment such as the Mojave Desert. NHTF delivers externally accessible and labeled locations to attach electrostatic discharge grounding straps. [7] In addition, the crew installed a Lightning Protection System around the High Bay. [7] This system ensures protection of the NHTF and equipment inside and is critical when dealing with explosives. In addition, the Air Force generated a siting plan approved by the Department of Defense Explosives Safety Board.[7] This plan authorizes the facility for a Net Explosive Weight up to 10 pounds of Hazard Division 1.1; or 50 lbs of Hazard Division 1.3; and 50 lbs of Hazard Division 1.4 based on the explosive potential of the chemical components of the propellants or ordnance used during integration and test activities.[7]

3.2.5 NHTF Summary

In summary, with all the facility upgrades in this project operational, the facility establishes a capability to perform missile defense interceptor vehicle static and hover tests incrementally verifying and validating vehicle related components and subsystems. This capability includes test facility infrastructure, qualified and trained personnel, process definition, control, and documentation, modular and open system architecture, and an operations safety system.[7] The facility delivers flexibility to integrate and test kill vehicles of diverse design and from various sources enabling maximum risk reduction for kill vehicles by gearing its methodology towards quality tests with rapid turn-around for a variety of customers/vehicles while reducing the customers' flight test risks and costs.

3.3 Propulsion Study

One of the key tenants of this test was to verify the propulsion subsystem performance. The propulsion subsystem consisted of a hypergolic bipropellant monomethylhydrazine fuel and nitrogen tetroxide oxidizer contained in propellant tanks, four cruciform divert engines, four bowtie attitude control engines, a helium pressurant system, and various burst discs, filters, and manifolding. The propulsion subsystem verification included a phased approach that originated back to previous static hot fire testing at NHTF in 2007 as shown in Figure 3.4.[3]

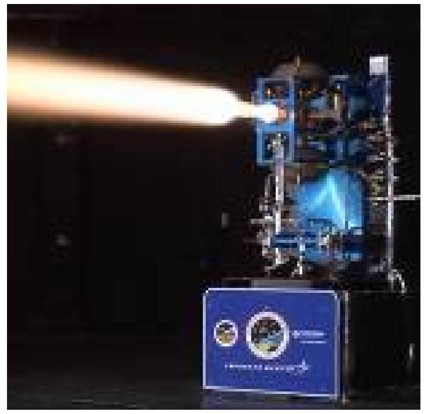

Figure 3.4 – Static Hot Fire Test[3]

In this static test, the team found the propulsion system experienced divert thruster combustion instability found in the divert control system.[6] This was a major issue in the design and a redesign to this system was broached. Upon inspection of the 2007 test results, the test team uncovered combustion instability within the divert thruster system.[6] In this case, the combustion instability exhibited a frequency response approximately equivalent to the first tangential mode of the combustion chamber as shown as the distinct peak activity below in Figure 3.5.[8]

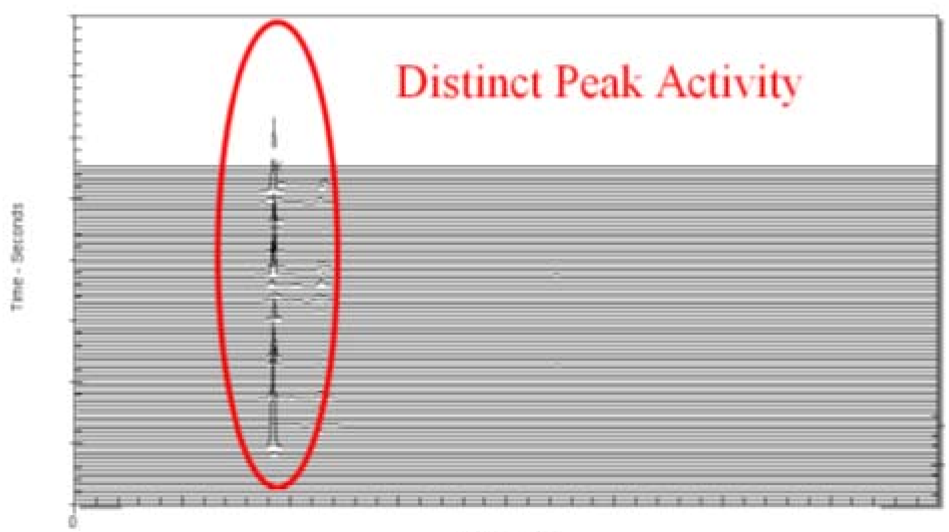

Figure 3.5 – Static Testing Combustion Instability (Normalized)[8]

As mentioned previously for the avionics components, the propulsion system design also need to avoid major frequencies avoiding resonance within the system. This resonance approach is extremely important since the resonance can produce metal fatigue and structural fracture causing the thruster and eventually the system to fail. This resonance approach can be seen using the non-homogeneous second order differential equation 3.1:[9]

$$\frac{d^2x}{dt^2} + \frac{c}{m}\frac{dx}{dt} + \frac{k}{m}x = \frac{F_0}{m}\sin \omega t. \tag{3.1}$$

Solving for this equation using the method of undetermined coefficients with $\omega^2 = \omega_0^2$ equation 3.1 becomes

$$\frac{d^2x}{dt^2} + \omega^2 x = \frac{F_0}{m}\sin \omega t \tag{3.2}$$

with the general solution to the associated homogeneous equation:

$$\frac{d^2x}{dt^2} + \omega^2 x = 0 \tag{3.3}$$

is

$$x(t) = c_1 \cos \omega t + c_2 \sin \omega t. \tag{3.4}$$

Since the non-homogeneous sine term is a solution to equation 3.3, equation 3.4 becomes

$$x_p(t) = b_1 t \cos \omega t + b_2 t \sin \omega t, \tag{3.5}$$

with

$$b_1 = \frac{-F_0}{2m\omega} \qquad \text{and} \qquad b_2 = 0. \tag{3.6}$$

Therefore, the general solution is

$$x(t) = c_1 \cos \omega t + c_2 \sin \omega t - \frac{F_0}{2m\omega} t \cos \omega t, \tag{3.7}$$

where the external force is

$$\frac{F_0}{2m\omega} t \cos \omega t. \tag{3.8}$$

Note as time increases, the vibrations described by the last term in equation 3.7 increases without bound and the external force is in resonance with the vibrating mass increasing the displacement to the point of failure.

Therefore, systems need to avoid increases in vibrations without bound. One method of achieving this is to decouple the frequency modes dampening the term in equation 3.8. Since the propulsion system is a flow system with fluidic propellants flowing into an injector combining the oxidizer with the fuel for a hypergolic combustion reaction, the flows can be manipulated to reduce the frequency of the fluidic system. This manipulation can be done by maximizing the use of the Strouhal number.[10] The Strouhal number is shown as

$$St = {fL}/{V} \quad , \tag{3.9}$$

where f is the frequency of pressure fluctuation, L is the characteristic length, and V is the inlet flow velocity. For tightly coupled flow areas where the length is minimal and approaching zero, an increase in the flow diameter greatly influences the flow area. Therefore, for our case the length is approximated as the flow diameter, d, giving

$$St = {fd}/{V} \quad . \tag{3.10}$$

Moreover, as determined by experimentation if the Reynolds number is smaller than a critical value, no more fluctuation occurred, and in a certain range of Reynolds numbers, the Strouhal number remained a constant.[11] Therefore, the oscillation frequency is linearly proportional to the flow rate and independent of the fluidic properties.[11] The fluidic flow system for the hover test contains a Reynolds number is in this stable regime. Therefore, the frequency becomes a direct function of the flow diameter shown in equation 3.11.

$$f = {StV}/{d} \quad . \tag{3.11}$$

This larger diameter naturally reduces the velocity of the fluid once in the injector tube deceasing the fluid velocity and dynamic pressure. Since the inlet velocity is constant in the established system and constant upstream system constraints. The frequency is solely a function of the flow diameter. This relationship can be seen in Figure 8.

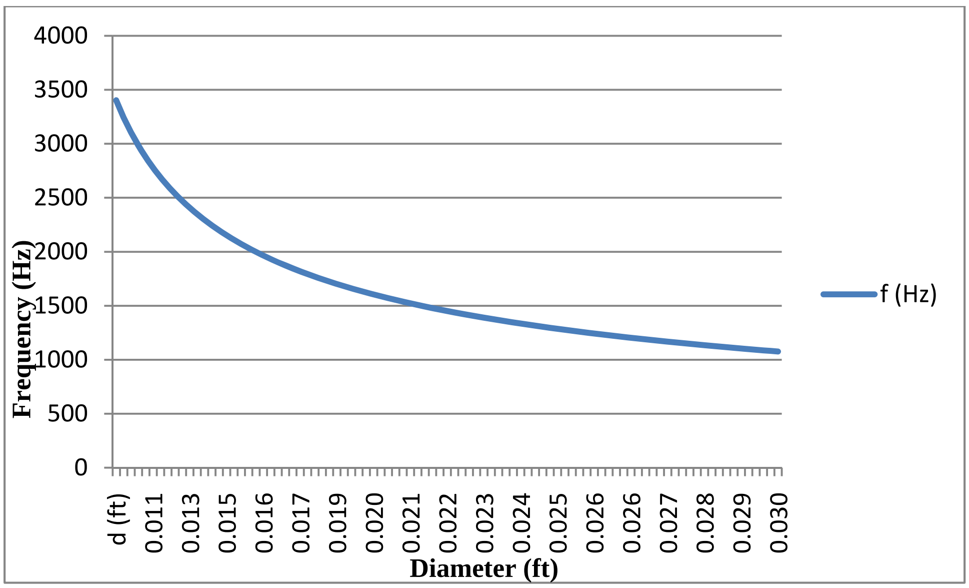

Figure 3.6 – Frequency vs. Flow Diameter

As Figure 3.6 indicates, an increase in the flow diameter changes the frequency. Therefore, by changing the frequency, the natural frequency modes of the thrust chamber are avoided, thereby decoupling the systematic frequencies and reducing the systematic response risk. This process needs to be modeled for each individual system and take into account the complete systematic frequencies and the natural frequencies of other key components that are susceptible to coupled resonance conditions. In addition to the diameter, the inlet flow velocity can also be modified if system constraints allow. However, in our case with a tested upstream flow system, the simple injector block modification was chosen instead of modifying the complete upstream system. Based on this theory, the divert injector system design was modified to reduce the fluid flow frequency below the first tangential mode of the combustion chamber.

CHAPTER 4

Results

4.1 Divert Thruster Testing

To prove the divert system complied with the theory and with the test constraints, the thruster was modified and tested. Two different thrusters were tested, one fully instrumented and one in the exact configuration as the hover test unit.[8] The fully instrumented unit had high frequency pressure transducers and thermocouples installed at key locations on the test article.[8] In this case, the combustion instability exhibited previously approximately equivalent to the first tangential mode of the combustion chamber was eliminated as shown below in Figure 4.1.[8]

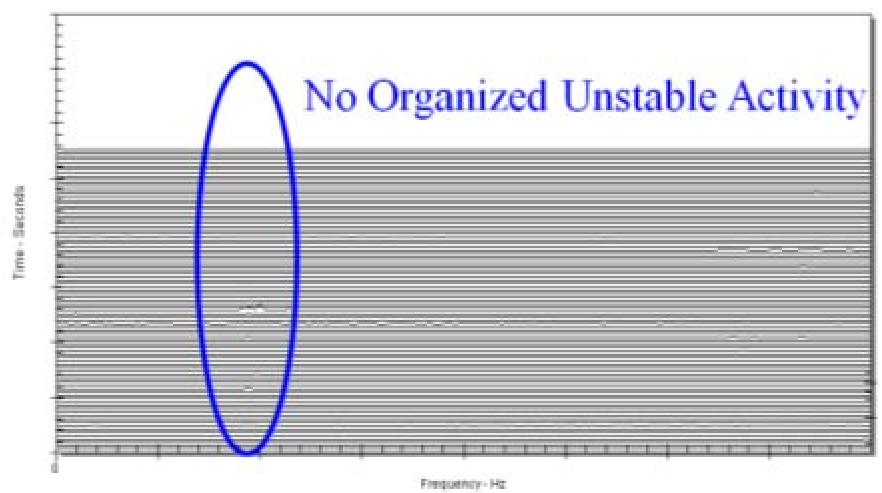

Figure 4.1 – Thruster Testing Combustion Instability Results (Normalized)[8]

A photograph of the actual hover test configuration test unit is seen Figure 4.2.

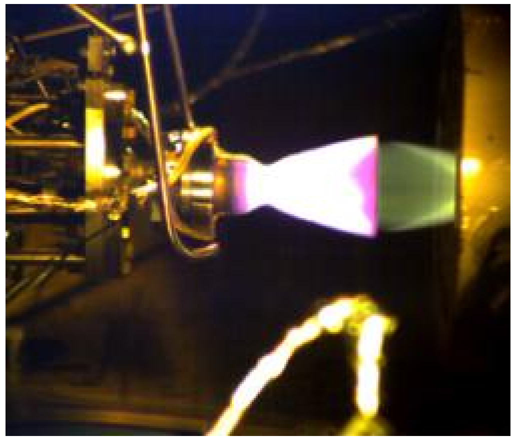

Figure 4.2 –Multiple Kill Vehicle Carrier Vehicle Thruster Test[3]

With the results verifying the thruster would survive the hover test environment and with the propulsion system completely compliant with all specifications verified through inspection, test, and analysis, the propulsion system was granted compliant for hover testing.

4.2 Hover Testing

The purpose of this hover test was to demonstrate a Hover Test Vehicle (HTV) capable of conducting closed-loop free-flight hover, delivering images of a reference target, and transmitting telemetry flight data.[12] The HTV lifted off at 1938 hours on December 2, 2008 from the National Hover Test Facility in Area 1-125E of the AFRL at Edwards Air Force Base, California.[12] The vehicle completed all success criteria by demonstrating hover flight within the defined hover volume, collecting key hover test data, and executing the test per the Master Countdown as shown in Figure 4.2.[12]

Figure 4.3 – Multiple Kill Vehicle Hover Test[12]

Prior to the start of the hover test, the NHTF crew mated the HTV with the Hover Launch Cradle and communicated with the STE via umbilical and wireless links.[12] When commanded by the STE, the umbilical demated from the HTV, and, after a pre-determined delay, the HTV commenced execution of a hover profile starting with liftoff from the cradle.[12] Telemetry data were sent via wireless connection to the STE with backup recording systems available on-board the vehicle.[12] Upon completion of the hover profile, the HTV fell into an area of the net not previously traversed.[12] Moreover, the test article tracked the target within 5 pixels, an extremely accurate track.[12] In addition, the Divert 4 thruster was not fired during flight as expected.[12] The total time of the flight was 20.1 seconds as commanded and the predictions from Monte Carlo analysis showed the axial drift being within +/- 2.5 meters during the flight, the test performed well within the predicted limits with a maximum of 0.2 meters of drift.[12]

Furthermore, during the hover profile the divert-2 engine or "Pogo" thruster executed its mission duty cycle to counter gravity and maintain a stable flight while performing all maneuvers. [12] The divert-2 engine performed liftoff with an avg. of 70% duty cycle and the hover profile with an average of 52.3%.[12] The DACS engines from the Hover Test were analyzed with accumulated on-times and cycles and the results fell within the predicted nominal on-times and pulses.[12] Moreover, the vehicle stability throughout the flight was assessed by verifying vehicle body rates and z position stability. The vehicle body rates fell within predicted Monte Carlo nominal bounds. Finally, vehicle azimuth and elevation pointing angles were measured on-board based on the pointing angles and visible camera image data. The measured azimuth and elevation angles met Monte Carlo predicted performance with over 100% margin. [12]

The vehicle performed the hover profile in four distinct waypoints allowing the HTV to hover in the middle of the hover volume while maintaining line of sight to the target located outside the net containment area. [12] The first and last waypoints represent the start and finish locations of the hover profile. Waypoints two and three are intermediate locations that the vehicle hovered to during execution of the hover profile. The hover profile was designed such that the vehicle will land in an uncharted area of the net at the conclusion of the profile. [12] The vehicle landed, as expected, at waypoint four and rolled to a resting point in the low portion of the net. [12] The vehicle executed within nominal predictions of the commanded path and waypoints. [12] The vehicle remained within the flight volume at all times and did not contact the facility containment net during flight. [12] The test was executed per established processes and procedures and the STE recorded all planned instrumentation data. [12]

Since the propulsion subsystem was a main focus of the test, an examination of the inlet and chamber pressures of Divert-2 showed that only 2 pulses exhibited rough combustion out of the 200 total pulses for Divert-2 at the first tangential mode of the combustion chamber. [12] The pulses occurred during liftoff and hover at waypoint 2. [12] The noise was evident in both fuel inlet pressure and chamber pressure. [12] The rough combustion had no adverse performance affects to the system nor did it exhibit any degradation to the hardware during post-test inspection. [12] Comparing the characteristics of these two pulses to similar pulses from the previous static hot fire test it was noted the measured amplitude of the combustion instability was decreased from 17.8% to 0.8%. However, the measured amplitudes are inconclusive since the reduced frequency response of the hover instrumentation may have attenuated the results. No deleterious effects were noted during the hover test or via visual inspection of the thruster hardware following the test.[12]

CHAPTER 5

Conclusions

The hover test demonstrated a closed-loop free flight and transmitted flight and images data back to the STE. The hover test was successfully performed on December 2nd, 2008 at the National Hover Test Facility. For the conditions investigated, the combustion instability presented was reduced from 17.8% in the static hot fire test to 0.8% in the hover test. [12] This reduction in combustion instability was verified by conducting risk reduction testing on the thruster prior to hover testing the entire test article and through the test article hover test. Using a fully instrumented thruster, all results verified the injector fuel manifold modification reduced the rough combustion seen in previous testing.[8] The success of the Hover Test also verified completion of the development and upgrades of a hover test bed. In addition, demonstration of using wireless telemetry shows the 802.11g standard is a viable alternative to the S-band telemetry system. The test met all test success criteria: achieve vehicle ignition and liftoff; achieve predefined hover position; maintain stable flight until commanded to first lateral maneuver; demonstrate closed loop tracking during all maneuvers; and test executed per established processes and procedures. [12]

There are many lessons learned from this test that are applicable for future testing. The lessons learned from this endeavor can be divided into distinctive themes for implementation: Better Communication, Establish Checks and Balances, Establish Functions and Responsibilities, Define Schedule and Critical Path, Identify Personnel and Training Needs, Define Requirements and Enhanced Design and Analysis, Identify

Vehicle and Facility Technical Upgrades and Test Facility Operations Flow.[12] By implementing these lessons learned in our future testing at the facility, future propulsion systems and the next generation interceptors will be appropriately tested ensuring all models and simulations are appropriately validated and anchored and flawless design risk reduction testing takes place prior to expensive flight testing.

REFERENCES

1. The Missile Defense Agency - U.S. Department of Defense. (April 9, 2010). The Missile Defense Agency. Retrieved from http://www.mda.mil.

2. Moulder, E. and Riley, R., personal communication on Multiple Kill Vehicle Hover Test Bed Statement of Work, December 16, 2006.

3. Williams, J. A., Beal, O., Paisley, E., Riley, R., Reeves, S., and Mapes, K., "Development of a Hover Test Bed at the National Hover Test Facility", October 10, 2007.

4. George, R., personal communication on Independent Scientific and Engineering Group Review of Hover Testing, June 2008.

5. Matlock, R.S., George, R. and Murphy, P., personal communication on Ballistic Missile Defense Kill Vehicle Hover Testing, June 2008.

6. Riley, R. and Kern, E., personal communication on MKV Hover Test Bed Component Development & Testing Hover Test Vehicle System Critical Design Review, April 10, 2008.

7. Joseph, A., Meyer, D., and Beal, O., personal communication on Hover Test Bed User's Guide, April 9, 2008.

8. Stephenson, D. and Kern, E., personal communication on Divert Thruster Hot-Fire Test Executive Data Review, August 8, 2008.

9. Derrick, W. R. and Grossman, S. I., "Elementary Differential Equations," Fourth Edition. 1997.

10. White, F. M., "Fluid Mechanics," Fifth Edition. 2003.

11. Yang, J.T., Lin W.C., Tsai, K.J., and Huang, K.J., US Patent 6860157 - Fluidic oscillator. March 1, 2005.

12. Moulder, E. and Riley, R., personal communication on Hover Test Final Report, December 19, 2008.