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MODELING AND SIMULATION TECHNOLOGY

A NEW VECTOR FOR FLIGHT-TEST

BY

MAJOR DAVID E. MILLER

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Disclaimer

The conclusions and opinions expressed in this document are those of the author. They do not reflect the official position of the US Government, the Department of Defense, the United States Air Force, or Air University.

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I also want to express my gratitude to my wife, Gayla, for all the patient support while I struggled with this research. She provided the laughs and smiles that made all the difference in ensuring success. Without her dedicated support, this project would not have been possible.

Abstract

In June of 1995, senior Air Force leadership led by Secretary Widnall and General Ronald Fogelman, Chief of Staff met to establish policy for the future of Air Force modeling and simulation (M&S). The result of this conference was the publication of *A New Vector* as a balanced strategy and a roadmap for Air Force M&S. The M&S roadmap in *A New Vector* is best compared to something with which the Air Force is very familiar—how to assess and invest in the capability of aircraft systems. Because aircraft systems assessment is the basic mission of flight-test, this thesis addresses the question: As design and engineering models increase in scope and complexity from the physical component level to complex systems, what are the capabilities and limitations of M&S for flight test?

In order to answer the research question three criteria were used to evaluate the results of each case study. First, the costs and benefits of M&S were compared with the tradeoffs required for not doing M&S. Second, the engineering validity of the M&S efforts was evaluated. Engineering validity is the determination as to whether the modeling data were sufficiently accurate to solve the problem at hand. Third, the comprehensiveness of each M&S effort was evaluated. For the purposes of this study, comprehensiveness is whether an M&S effort had sufficient scope to solve the entire problems. An M&S effort that *completely and accurately* predicted the experimental outcome of flight-test was comprehensive.

The process used for answering these questions was a systematic examination of three case studies. The first case covered M&S at the physical component level, and

looked at how computational fluid dynamics was used to solve a stores separation problem on the B-1B. The second case was an examination of the VISTA in-flight simulator as a tool for modeling closed-loop control systems. The third case examines the role of M&S in designing and flight-testing the Boeing 777.

All three cases discussed in this research have made significant progress towards meeting the challenges set out by senior Air Force leadership in *A New Vector*. Although M&S is not free, it is usually more cost-effective than testing alone. The engineering validity of M&S was excellent in all three cases. The accuracy of the models was equal to or better than traditional engineering methods. However, as the modeling efforts became more complex, it was not possible to build comprehensive models of Boeing 777 with the current state of the art. As M&S becomes more integrated into the aircraft design process, the Air Force must better understand the capabilities and limitations of M&S before flight-testing.

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Chapter 1

Envisioning the Future of Flight-Test with Modeling and Simulation

Never again will the United States ride the coattails of other countries in the progress and development of the aeronautical art...

President Harry Truman
June 25, 1951

As Commanding General of the Army Air Forces during World War II, General Hap Arnold not only saw the need for a separate Air Force, but he was also concerned about the role of technology and scientific research in developing airpower. After achieving a separate Air Force in 1947, General Arnold wrote: “I have yet another job. That is to project myself into the future...and determine the steps the US should take to have the best Air Force in the world 20 years hence...”¹ General Arnold’s intention was clear. The United States would maintain the most capable and technologically advanced Air Force in the world. General Arnold’s vision continues to have a profound influence on the Air Force today.

Almost fifty years later, senior Air Force leadership continues General Arnold’s tradition by projecting into the future and determining the steps necessary to be the best Air Force in the world. Fortunately, the US Air Force currently holds the technological

lead in almost every aspect of the aeronautical arts. However, rapid advances in information technology threaten this lead by reducing the lead-time required to go from initial concept to fielded military capability. In order for the Air Force to sustain its technological lead in the aeronautical arts, it must now move to the forefront of the information technology revolution as well.

Information technology, especially Modeling & Simulation (M&S) provides powerful engineering and design tools to shape the future of airpower. Present trends indicate that M&S technology will become an increasingly powerful aspect of aeronautical engineering, design, and flight-testing. Currently computer speeds are doubling every 18 to 24 months while the costs of computing power are being halved during the same period. This trend is likely to continue for the near future. Therefore, senior Air Force leadership decided to take the steps necessary to move the US Air Force to the forefront of M&S technology.

In early June 1995, the senior Air Force leadership, led by the Secretary of the Air Force Sheila Widnall and the Chief of Staff, General Ronald Fogleman, gathered to set *A New Vector* for the future of Air Force M&S. The result of this meeting was a “roadmap” for the future of Air Force M&S capabilities in the 21st century. Senior leadership has endorsed the Air Force M&S road map—as a balanced strategy for a clear vision of the future.² With these actions, the Air Force took a critical step toward having the most technologically advanced Air Force in the next century.

Notes

¹ *Vision—The History and Mission of Arnold Engineering Development Center*. (Arnold AFB, TN.: Public Affairs Office, Arnold Engineering Development Center. February 1994), 2.

² Air Force Four Star Commission on Modeling and Simulation. *A New Vector: Air Force Modeling and Simulation* (Washington, DC: Government Printing Office, 1995), 1.

Since the publication of *A New Vector*, the aeronautical arts have made significant advances as the result of M&S technologies, and the Air Force has continued to move a little closer to the vision outlined by senior leadership. The vision of *A New Vector* is based on a four-tiered roadmap that comprises the elements of vision, quality, people, and infrastructure. The framework for this roadmap is shown in Figure 1 below. While this roadmap draws attention to critical elements, it is only notional and not intended to provide detailed instructions or specific examples.

The *New Vector* roadmap provides a broad view of current M&S initiatives. It provides the overview and lays out the Air Force's institutional priorities. However, *A New Vector* does not provide specific guidance about how and where the Air Force must begin grappling with M&S technologies. Despite the broad policy guidance in *A New Vector*, most Air Force M&S efforts remain specialized engineering tools. Therefore, the Air Force cannot fully exploit the remarkable synergies of M&S technologies for complex systems.

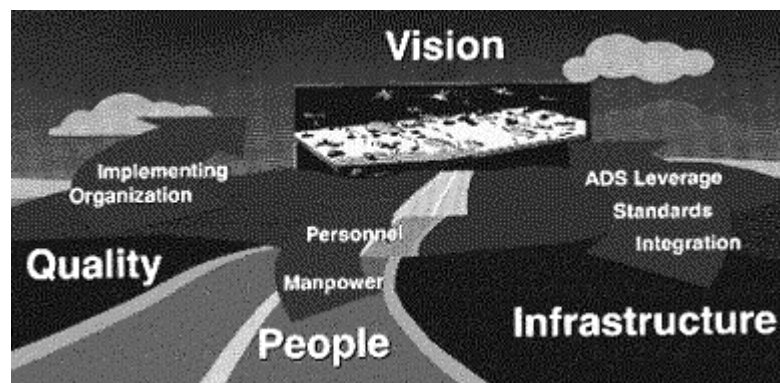


Figure 1: The Modeling and Simulation Roadmap
from *A New Vector*

This thesis answers the question as to how and where the Air Force must begin grappling with the specifics of integrating M&S technology into the process of designing

and flight-testing aircraft. M&S is already a powerful engineering and design tool. Flight-test is the final evaluation of the entire aircraft design and production process, and aircraft systems assessment is the basic mission of flight-test. As M&S becomes more integrated into the aircraft design process, the Air Force must understand the capabilities and limitations of M&S before flight-testing. Therefore, this thesis addresses the question: As design and engineering models increase in scope and complexity from the physical component level to complex systems, what are the capabilities and limitations of M&S for flight-test?

The process used for answering these questions is a systematic examination of three case studies. The case studies were chosen because together they cover a wide spectrum of M&S capabilities from physical component models to models of highly complex systems. Each case illuminates some of the extraordinary capabilities as well as the inherent limitations of M&S. The cases also show that M&S is now a critical aspect of major weapons system development, and rapid technological advances in M&S are making a profound impact on the way weapons systems are being developed and tested.³

In order to answer the research question three criteria will be used to evaluate the results of each case study. First, the costs and benefits of M&S will be compared to the tradeoffs required for not doing M&S. Second, the engineering validity of the M&S efforts will be evaluated. Engineering validity is the determination as to whether the modeling data were sufficiently accurate to solve the problem at hand. Third, the comprehensiveness of each M&S effort will be evaluated. For the purposes of this study, comprehensiveness is whether an M&S effort has sufficient scope to solve the entire

problems. An M&S effort that *completely and accurately* predicts the experimental outcome of flight-test is comprehensive. On the other hand, an M&S effort that makes errors of omission or does not account for significant experimental results is not a comprehensive model.

The first case study demonstrates the capabilities and limitations of M&S at the physical component level. In this case, computational fluid dynamics (CFD) was used to solve a B-1B flare strike problem by modeling the aircraft and the flare as physical components in the flight environment. This problem restricted flare operations and significantly reduced the combat capability of the B-1B weapons system.⁴ Yet, M&S and played an essential role in augmenting flight-test efforts and resolving the problem — restoring the fleet to full operations.

The second case looks at the Variable Stability In-flight Test Aircraft (VISTA). The VISTA is a highly modified F-16 fighter aircraft that can actually simulate the handling qualities of another aircraft in-flight. The VISTA aircraft uses M&S technology to alter its flying qualities for the pilot. The software and methodology is very similar to a ground simulator, except that the variable stability system is sophisticated enough to change the actual response of the aircraft to various control inputs. In contrast to the B-1B flare strike case study that modeled physical components, the VISTA modeled a complete aircraft with man-in-the-loop interactions, which significantly increased the complexity of the M&S effort.

Notes

³ Department of Defense (DOD) Directive 5000.59. *Department of Defense (DOD) Modeling and Simulation Management*.4 January 1994.2.

⁴ By order of the ACC/DO March 1995.

The VISTA was used to help design and test the F-22 flight control system. The fly-by-wire flight control system on the F-22 is the most sophisticated flight control system ever engineered. The F-22's flight controls have incorporated state of the art digital control theory to improve its flying qualities as well as make the fly-by-wire system robust and failure tolerant. Fly-by-wire systems are themselves model-following control systems. Therefore, the desired response of the aircraft is written into the computer code as a model. The VISTA allows that code to be flight-tested carefully in order to find software "bugs," improve flying qualities, and to increase the control systems failure tolerance. Because the VISTA has a redundant flight control system, flight-testers can test fly-by-wire control systems without endangering a pilot or valuable prototype aircraft.

The third case study examines how the Boeing Company used M&S technology to make radical changes in how they design, produce, and flight-test airplanes. The Boeing 777 was the first commercial jet completely designed and prototyped by using M&S technology. The changes wrought by M&S technologies were very dramatic and encompassed many areas, including technical, organizational and administrative changes. Although the technical innovations were numerous, the Boeing 777 project was unique because of the central role of M&S technology in the design, construction, and testing of the airplane.

Boeing used M&S technology to completely design and prototype an aircraft in cyberspace. Instead of engineering drawings, the Boeing 777 design team used three-dimensional solid modeling technology. The software used for this effort was CATIA (Computer-Aided, Three-dimensional Interactive Application) developed by Dassault

Systems of France. The Boeing 777 division used more than 2,200 CATIA workstations networked to a mainframe computing cluster. The project was the largest ever computer-aided design (CAD) project. Concurrent engineering was also an integral part of Boeing's M&S effort. Each "Design/Build" team interacted extensively with the others through their CATIA workstations and coordinated design changes by sharing three-dimensional models that were used by all the other teams. These teams included representatives from design, engineering, manufacturing, customers, and suppliers.

In the past, Boeing designers had always built a full-scale non-flying mockup of the complete aircraft to check form, fit, and interference. Since various aircraft systems were designed independently, it was necessary to make painstakingly precise physical mockups. This practice was very expensive and the various required mockups of the Boeing 777 were estimated to have cost more than \$22.5 million. The mockup was also used to check accessibility of all the parts for maintenance work. However, with a three-dimensional database that everyone on the design team could use simultaneously, prototype phase could be bypassed in favor of going directly into production.

Because the production aircraft was built to conform to computer models, the B-777 flight-test program was essentially a model verification program. This case study is an extremely important example of how M&S technology can cause enormous impacts from the initial design through flight-testing. There are many lessons the Air Force can learn from the Boeing experience in order to implement the policy guidance from *A New Vector*.

Each case in this research is an important example of M&S when considered alone. However, the implications for the future of aircraft design and flight-test are enormous

when the capabilities illustrated by each case are considered together. M&S is now an essential part of the total aircraft system design, engineering, and test effort. As part of the roadmap from *A New Vector* for the 21st century, the Air Force will be integrating M&S into the engineering, design, and flight-test in order to develop 21st century airpower.

Chapter 2

Case Study One-Physical Component Modeling of the B-1B Flare System

Testing is the conscience of acquisitions...

Honorable Phillip E. Coyle III
Undersecretary of Defense

Introduction

This case study covers a major success of M&S at the physical component level. The case involved a problem concerning flare strikes that the B-1B operational fleet was suffering. The damage caused by the flares striking the aircraft restricted flare operations and caused a flight safety problem. Because the flare strikes seemed to be random occurrences, classical flight-test techniques could not solve the problem alone. M&S techniques were essential to finding the underlying causes of the flare strikes. Specifically, computational fluid dynamics (CFD)—a sophisticated method of modeling the forces acting on a body in a flowfield— was used to resolve the problem and restore the B-1B fleet to full operations.

Historical Background of the B-1B Flare Problem

The B-1A was originally designed as a high altitude, supersonic, strategic nuclear bomber. President Jimmy Carter canceled the B-1A program in June 1977, but President Ronald Reagan later revived the program as the B-1B in October of 1981. However, the

mission changed due to emerging threats in the early 1980's and the B-1B took on the role of a low-level strategic nuclear bomber with high subsonic ingress and egress capabilities, as well as a supersonic dash capability.⁵ The B-1B defensive systems were redesigned for its new mission, with the primary aircraft threat now evolving from a radar guided missile to a look down infrared (IR) missile attack. Therefore, one of the important defensive systems retained from the B-1A program was the MJU-23/B IR flare. The MJU-23B flare was designed to defeat both the surface-to-air and air-to-air heat-seeking missiles employed by potential adversaries (see Figure 2: MJU-23/B Flare Used on the B-1B).

Subsequent to this design point, the mission of the aircraft was again changed to a conventional bombing role. As a conventional bomber, the B-1B must operate without a nuclear “lay-down” of enemy air defenses from ICBM attacks, and the aircraft must be able to survive in a high threat environment. Because of the change to a conventional mission, B-1B tactical doctrines were changed to reflect the new threat environment and new tactics were developed.⁶ Consequently, Air Combat Command (ACC) substantially improved its training scenarios to reflect the B-1B's evasive combat maneuvers and the anticipated flare use. These factors all contributed to the increased use of flares, as well as the resulting aircraft strikes.

The B-1B operational fleet began suffering strikes from the MJU-23/B defensive flares with an alarming frequency from 1994 through early 1995. These flare strikes took two different forms: “major” strikes and “minor” strikes. Major strikes were defined as

Note

⁵ Major Richard A. Stuckey and Major Craig T. Edkins, “B-1B Flight-Test Update,” *Proceedings of the 39th Symposium of the Society of Experimental Test Pilots*, September 1995.

any flare strikes that produced large holes, burns, or damage to composite surfaces. Minor strikes were defined as any strike that produced only scuffs, paint scrapes, or small punctures in the skin. Generally, major strikes only occurred on the horizontal and vertical tail surfaces, while minor strikes were found all along the upper surface of the fuselage and over the entire empennage area. As a direct result of these strikes—and their increasing frequency—the ACC Deputy for Operations (ACC/DO) ordered the termination of all training activities with live flares in March 1995.⁷ The training moratorium was to stay in effect until a solution to the problem could be discovered and implemented.

The B-1B System Program Office (SPO) at Wright-Patterson AFB, OH and the B-1B System Sustainment Office (SSO) at the Oklahoma Air Logistics Center (OC-ALC) at Tinker AFB, OK were notified and began the effort to solve this problem. Coincidentally, OC-ALC had already begun work on a MJU-23/B flare modification program with the flare item managers at the Ogden Air Logistics Center (OO-ALC), Hill AFB, UT and with Tracor Corporation in San Ramon, CA, the flare manufacturer. The flare modification program was primarily focused on production and cost-reduction issues. However, the increasing flare strike threat to the fleet aircraft provided an opportunity for a synergized approach.

OC-ALC arranged for flight-test activity with the 419th Flight Test Squadron (FLTS) at the Air Force Flight Test Center (AFFTC), Edwards AFB, CA, which served as the B-1B Combined Test Force (CTF). Both the OC-ALC and the CTF's first major objective was to determine and model the trajectory of the flares, thereby identifying

Notes

⁶ T.O. 1B-1B-1-2, *Offensive/Defensive Systems Officers Flight Manual*, 15 Aug 94.

potentially risky flight conditions. In order to accomplish this goal, the CTF also requested M&S support from the Arnold Engineering Development Center (AEDC) at Arnold AFB, TN. AEDC had extensive experience in M&S and had recently completed a stores separation analysis for the F-22 program using CFD modeling methods that were applicable to the B-1B flare strike problem.

The B-1B CTF also requested support from the Naval Air Warfare Center, Weapons Division (NAWCWPNS) because of their extensive flight-test experience with flare trajectory mapping and modeling. These six organizations (OC-ALC, OO-ALC, CTF, AEDC, NAWCWPNS, and Tracor) quickly integrated themselves into a cohesive team. The team combined flight-test techniques, practical engineering experience, and state of the art CFD modeling methods to determine the cause of the flare strikes on the B-1B fleet aircraft.

The use of the MJU-23/B flare was unique to the B-1B program —no other weapons system in the world employed anything like it. Each cylindrical flare pellet weighed over 3.25 pounds. The flares were deployed from eight dispensers with twelve flares each, which were located on the top of the aircraft just aft of the crew compartment (see Figure 3: Flare Canister Locations on the B-1B).⁸ The flares were loaded into individual canisters that were equipped with an ejection cartridge, as well as seals and covers for environmental protection in flight and on the ground. These canisters were then loaded into the dispensers in the maintenance backshops, and the dispensers were loaded onto the aircraft at the flight line.

Notes

⁷ By Order of ACC/DO, 1 March 1995

⁸ T.O. 1B-1B-1-2, *Offensive/Defensive Systems Officers Flight Manual*, 15 Aug 94.

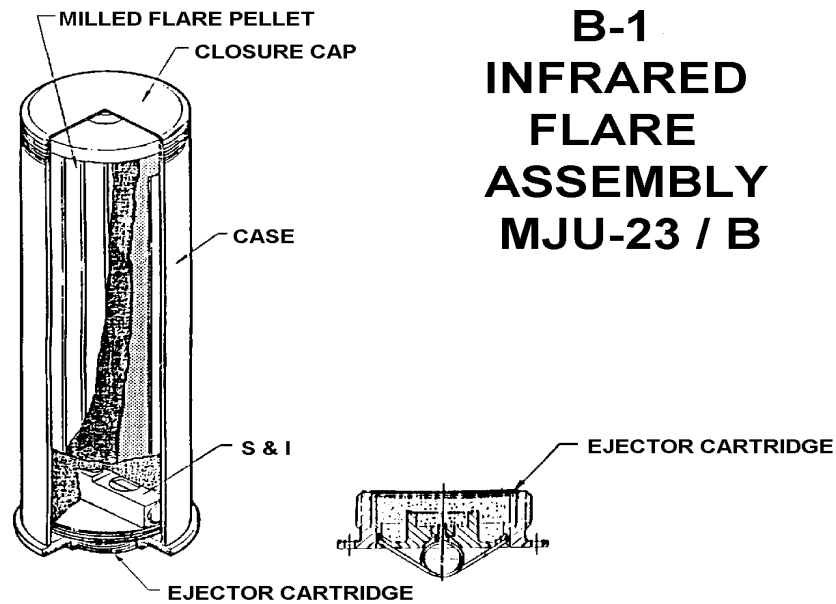


Figure 2: MJU-23/B Flare Used on the B-1B

The original MJU-23/B flare design specification, created during the original B-1A program, dictated that the flare ejection velocity remain between 80- feet per second (fps) and 120-fps.⁹ The flare ejection velocities were measured for specification compliance during sled track tests at Hollomon AFB in the early 1980's. The flares were also flight-tested successfully at Edwards in straight and level flight during the same period. None of these tests indicated any difficulties.¹⁰ However, the design specifications and flight-test methods were designed for the non-maneuvering B-1A at high altitude instead of the low-altitude, high speed, and aggressive maneuvers the B-1B used in the 1990's. New

Note

⁹ 419 Flight Test Squadron, "MJU-23B Flare Trajectory Analysis Test Plan," Edwards AFB, CA. March 1995. 23.

¹⁰ 419 Flight Test Squadron, "Test Director's Flight Test Logs" Edwards AFB, CA. November 1983. *microfiche*.

flight-test techniques would be required to model flare trajectories relative to a maneuvering aircraft.

Experimental Techniques

The original request for flare testing from OC-ALC to the CTF was only to evaluate a seemingly insignificant flare modification. Approval for such a test was obtained at AFFTC. However, a secondary objective soon followed to model flare trajectories, with a particular request to observe and record any damage to the aircraft during the flight-test program. The CTF then investigated the background of this secondary request. This investigation revealed the history of the flare strikes mentioned previously. The flight-test plan was reviewed and the CTF determined that this new objective took the project well beyond both the technical and safety scope that had been approved by AFFTC.

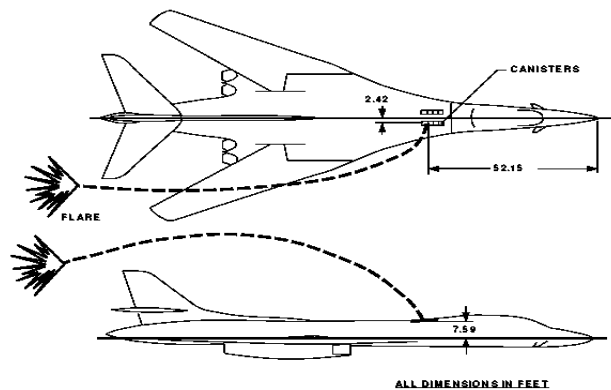


Figure 3: Flare Canister Locations on B-1B

The flight-test plan was rewritten to include the flare damage investigation, but the CTF quickly realized the need for analysis before they could safely determine the cause of the problem. The CTF requested that OC-ALC enlist analytical support, realizing the need to gain a technical understanding of the problem facing them. OC-ALC responded

by contracting with AEDC and its support contractor, the Sverdrup Corporation, to perform M&S of the flare trajectories using CFD.

The CTF tasked AEDC to evaluate two specific aspects of the flare strikes on the B-1B empennage. First, AEDC was tasked to look at the flowfield around the aircraft and to identify any anomalies that may have been depressing the flare trajectory, such as wing tip vortices. Second, AEDC was tasked to look at maneuvering flight in order to determine if any unusual characteristics appeared in the “aggravated” flowfield. In order to accomplish these tasks, AEDC took a partial B-1B CFD model that was used for a previous weapon separation evaluation, modified it to include the empennage, and developed flowfields for the complete aircraft. Next, AEDC developed a flare model and evaluated its burning characteristics. The flare model was then superimposed onto the B-1B flowfield in order to calculate the flare trajectories.

The CTF also requested support from NAWCWPNS for a special camera system to capture the flare trajectories. NAWCWPNS specialists used their recent flare testing experience to design and create a unique, self-contained, two-unit camera package that was built inside an empty flare dispenser. The package was mounted in the forward, left-hand dispenser bay of the B-1B flight-test aircraft. A narrow field-of-view (NFOV) camera and a wide field-of-view (WFOV) camera were mounted to provide maximum film coverage of the flare deployments.

These cameras were then calibrated to provide the Y-Z flare position information relative to the aircraft. In addition, a NAWCWPNS QF-4 was equipped with an Airborne Turret Infrared Measurement System III (ATIMS III) and flown in formation with the test aircraft to capture the flare’s X-position data relative to the B-1B flight-test aircraft.

The ATIMS III was a pod-mounted instrument and data acquisition system that housed television cameras, IR spectrometers and imaging systems, and up to four missile seekers as required by individual test customers. The flight-test engineer in the back seat of the QF-4, who was assisted by a video and graphics display on a small television monitor, operated the turret. During post-test analysis, the NFOV, WFOV and ATIMS images were time-correlated and reduced to provide center-of-flare position data with the extraordinary accuracy of ± 1 ft.

In order to capture the flare trajectory data, the QF-4 flew off the right wing of the B-1B, at co-altitude and positioned back at the 4-5 o'clock position. The B-1B Defensive Systems Officer (DSO) would deploy a flare at the specified Mach number and altitude. The onboard cameras automatically sequenced to the "run" position with the firing pulse. The ATIMS III was manually activated on a countdown from the B-1B DSO. Flight-test conditions varied as a function of increasing dynamic pressure from 0.70 Mach (M) and 20,000 ft. above mean sea level (MSL), to 0.95 M and 3,000 MSL. The original flare test plan called for straight-and-level points, as well as some constant bank angle points.

However, this plan was altered significantly during the course of the flight-test program. Because of the knowledge of the flare trajectories gained through M&S, hazardous flight conditions could be predicted and avoided. This was a significant change in the test team's approach to the problem. At first, the team was collecting data in order to build a flare trajectory model. However, the initial model was very accurate—within 2 feet—that the model was used to determine the next flight-test point. In this case, M&S did not take the place of flight-test. Flight-testing was essential because it was the only way to collect "truth data" for the M&S effort. However, flight-testing could not be

accomplished safely independent of the trajectory model provided by CFD analysis. In this case, M&S were essential for safely accomplishing the test objectives.

Modeling and Simulation Methods

The objective of M&S was to investigate the cause of the flare strikes on the B-1B empennage by modeling the flowfield around the aircraft and then by evaluating the effects of specific aircraft maneuvers on the flowfield. In both cases, the intent was to determine if the flowfields depressed the flare trajectory into the aircraft and then to determine the specific causes of lower trajectories.

The original M&S plan for this problem was to develop sets of flare trajectories for given sets of aircraft flight conditions and flare ejection conditions. The tools to accomplish this task included CFD analysis, engineering methods, and solutions to the six degree-of-freedom (6-DOF) equations of motion. CFD was used to determine the aircraft flowfields. Engineering methods were used to develop an analytical model of the aerodynamic characteristics of the flare. The flare ejection velocities were added to these models, and then all of these models were used as inputs to the 6-DOF equations of motion to generate the flare trajectories in the presence of the B-1B flowfield.

The AEDC team began by modifying a previously used B-1B CFD model created for a weapons separation program. An empennage was added to the original model, which was not required for the weapons separation analysis. Input modules were also changed to accept CFD initial conditions instead of wind tunnel inputs.¹¹ The trajectory data from the NACWPNS cameras provide the initial baseline and calibration data for the CFD

Note

¹¹ Air Force Instruction (AFI) 16-1001. *Verification, Validation, and Accreditation (VV&A)*, draft. *This draft AFI was subsequently published 1 June 1996.*

model. NACWPNS data was also used to validate the predictions of the CFD model as the dynamic pressure was increased in a build up approach during the flight-test.

This CFD model used a computational approach known as the chimera overset mesh methodology. The term “chimera” applied to the scheme because of its similarities with the Roman mythological creature that was created from parts of several other animals. Like its mythological namesake, the chimera scheme took component flowfield grids around the aircraft, such as the wings, fuselage, nacelles, empennage and then connected them into a system of relatively simple overlapping computational meshes to construct a complete model. In this case a total of 22 meshes, and over 1.1 million total mesh points were generated to cover half of the aircraft, and then the principle of symmetry was used to cover the other half (see Figure 4: B-1B Computational Mesh System). As the CFD flowfield solution was initiated in the computer, the boundary conditions for each point downstream in the meshes were interpolated from the flow properties in the overlapping meshes.

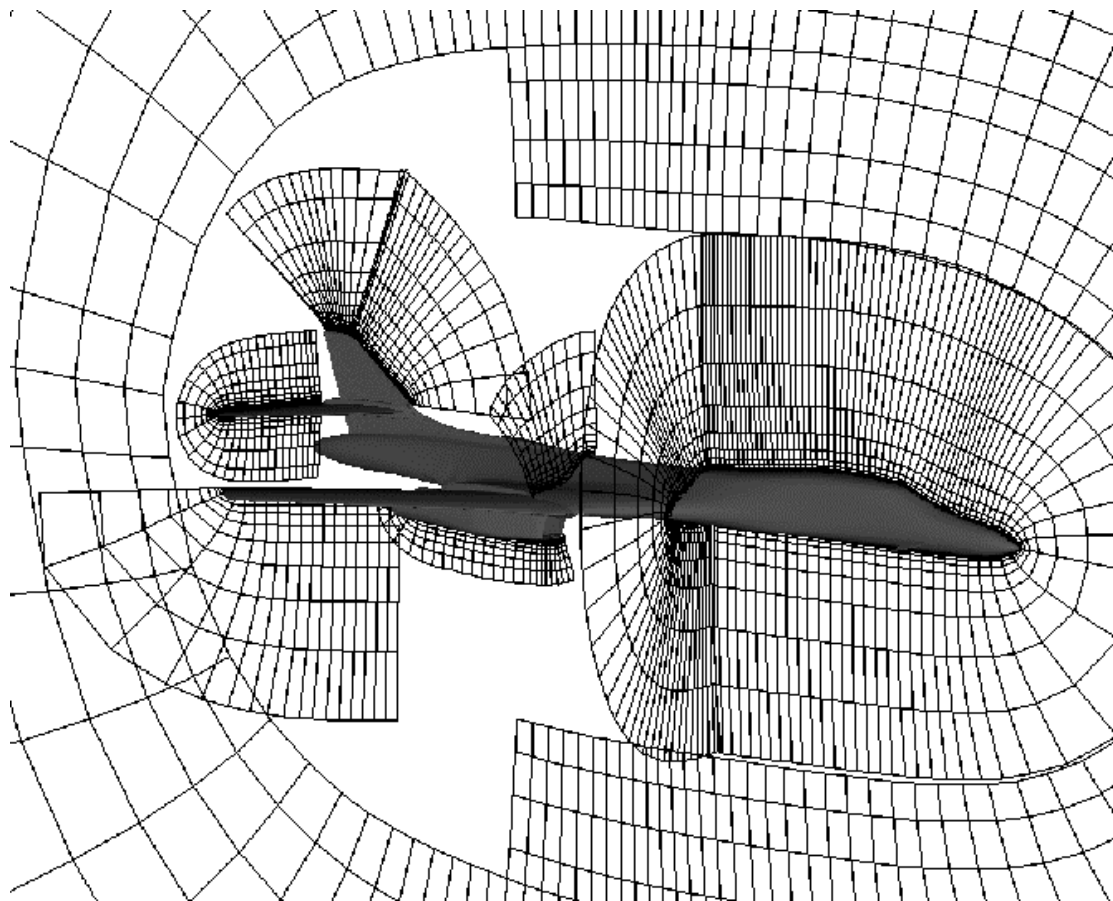


Figure 4: B-1B Computational Mesh System
(Meshes Coarsened for Clarity)

Three significant, simplifying assumptions were also made during this early phase of the M&S effort. First, the assumption of inviscid flow was made, which considerably simplified the problem. This assumption was based on the results of a previous weapons separation analysis, which had originally used fully viscous flow model. The previous analysis indicated there were no significant viscosity effects over the top of the aircraft. Therefore, the coefficient of viscosity set to zero in the computer model and the simulations were run again as inviscid (Euler) equations, which yielded similar results to the fully viscous Navier-Stokes equations. The second simplifying assumption was flowfield symmetry about the X-Z (vertical) plane of the aircraft was assumed for cases

involving no sideslip or roll rate. For those cases with roll rate or sideslip, the full aircraft model was used to account for the cross-flow components.

The third modeling assumption was to model the flare as a cylinder in the flowfield. In order to validate this assumption, the first consideration was to determine whether the burning of the flare contributed significantly to the trajectory of the flare, either from loss of mass or from changing shape. Tracor provided test data, which indicated that approximately 3 percent of the flare mass was consumed during the 0.3 to 0.5 seconds required for the flare to pass the rear plane of the vertical tail.¹² Because such a small portion of the flare consumed during this period, mass flux could not significantly affect the flare trajectory either. Once the non-burning flare model was assumed, the flare trajectory problem became a “classic” cylinder in a fluid stream described in most

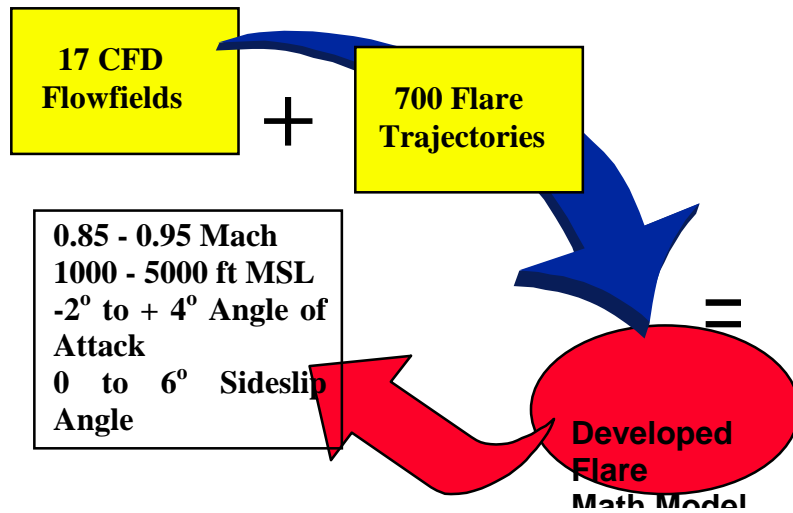


Figure 5: Flight Conditions Modeled

Note

¹² Mr. Neal Brune, Tracor Corporation, to B-1B Sustainment Office, letter, subject: MJU-23B Defensive Flare Technical Specifications, 1 November 1996.

textbooks on fluid dynamics¹³ (see Figure 6: Model of the MJU-23/B Flare Pellet).

AEDC modeled the flare using a semi-empirical aerodynamic coefficient prediction program that had been generated for other projects—primarily weapons separation evaluations. This flare model was then placed into the aircraft flowfield model. At this point, the modeling effort was complete and the computer began computing flare trajectories for simulated flight conditions.

In total, the AEDC team developed seventeen different flowfields. The primary variables in these flowfields were angle-of-attack, sideslip, mach, and roll rate. These flowfield models were then used to generate over 700 different flare trajectories (see Figure 5: Flight-Test Conditions Modeled). Once these trajectories were validated by flight-test, a linear Taylor series model was developed. The Taylor series model defined the point in space where the flare would pass the trailing edge of the tail for a given set of flight parameters. The Taylor series model tremendously reduced the computer resources required but was only useful because it had been validated with the full CFD solutions which had in turn been validated by flight-test.

As the completed computational model developed solutions, these solutions were compared against the results that had been generated during the early portion of the flight-test effort. The success of the M&S effort was immediately apparent. The statistical variance between the actual flight-test results and the model results for a given set of ejection velocities and flight conditions were negligible for both straight and level flight and steady banked flight. One important conclusion became immediately apparent from the results at this early stage. As long as the flare ejection velocity was within its

Note

¹³ John D. Anderson, *Introduction to Flight*, 3rd ed. (New York: McGraw-Hill, 1989),

specified design conditions, the flares could not physically hit the tail of the aircraft during straight and level flight or steady banked flight (see Figure 7).¹⁴

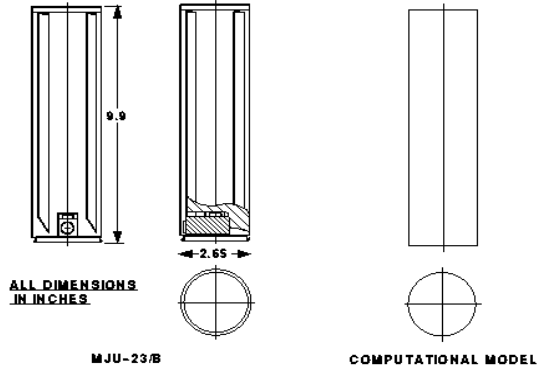


Figure 6: Model of MJU-23/B Flare Pellet

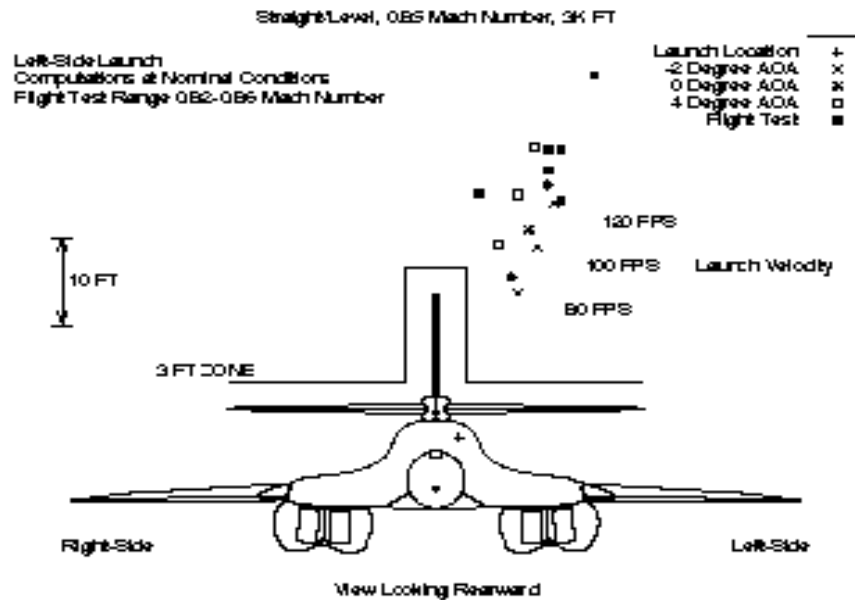


Figure 7: Comparison of Flight-test Data with Computational Model for Straight and Level Flight

Notes

133-135.

¹⁴ Major John H. Humphries and Major David E. Miller, “B-1B/MJU-23B Flare Strike Test Program,” *Proceedings of the 40th Symposium of the Society of Experimental Test Pilots*, September 1996

Engineering Results

The revelation of no flare strikes in level flight led to a complete revision of the flight-test plan to include various maneuvers.¹⁵ Since the number and style of defensive maneuvers was practically unlimited, choosing “operationally representative” maneuvers became the next issue. Fully repeatable maneuvers, including rolls and bunts, were required and devised to validate the maneuvering models at AEDC. Both deterministic (flare trajectory) and stochastic (random maneuver) data were required. In addition, the CTF began to record a series of “gun-jinks” to provide insights into the transient flowfield characteristics during defensive maneuvers.

The M&S effort resulted in increased test efficiency during this phase of the program. The CFD models permitted the team to use a “predict-fly-analyze” approach, instead of a “fly-fix-fly” approach. The AEDC team analyzed these maneuvers for angle-of-attack, roll, and airspeed content to create similar maneuvers in the computer model. Flares were deployed during rolling maneuvers using the procedures in the initial flight-test program.

However, this effort was cut abruptly short when the QF-4 chase plane could not visually verify that the flares were not actually striking the tail during the roll. On four out of twelve events, the chase plane had to rejoin on the B-1B to investigate apparent strikes.¹⁶ Although none of the flares actually struck the aircraft, the flight-test team readily recognized that continuing the tests would be hazardous. Therefore, flight-tests

Note

¹⁵ 419 Flight Test Squadron, “MJU-23B Flare Trajectory Analysis Test Plan,” Edwards AFB, CA. March 1995. 33.

were suspended until M&S could provide some critical answers. In the meantime, AEDC agreed to continue M&S work with the rolls and other maneuvers using the data points already obtained to validate the models.

In order to handle the maneuvering flight requirement in the computer model, several tools at AEDC had to be modified and then applied. The first of these tools was a two-body motion program originally developed for the F-22 program to investigate the effects of a rolling aircraft launching a missile. This model was modified to accept CFD inputs instead of wind tunnel inputs and the respective aircraft and “weapon” model changes were made. The second tool was a modeling scheme called “dynamic flowfield interpolation” that was developed at AEDC for an F-15E weapons separation program. This technique, which was validated with flight-test results, allowed the modeler to add dynamic flight parameters on top of a constant aircraft flowfield to generate a “maneuvering” aircraft.¹⁷

Notes

¹⁶ Naval Air Warfare Center Point Mugu. *Flight Tests of MJU-23/B Flares (U)*. In-house production. 40 min., 1996, videocassette.

¹⁷ Air Force Instruction (AFI) 16-1001. *Verification, Validation, and Accreditation (VV&A)*, draft

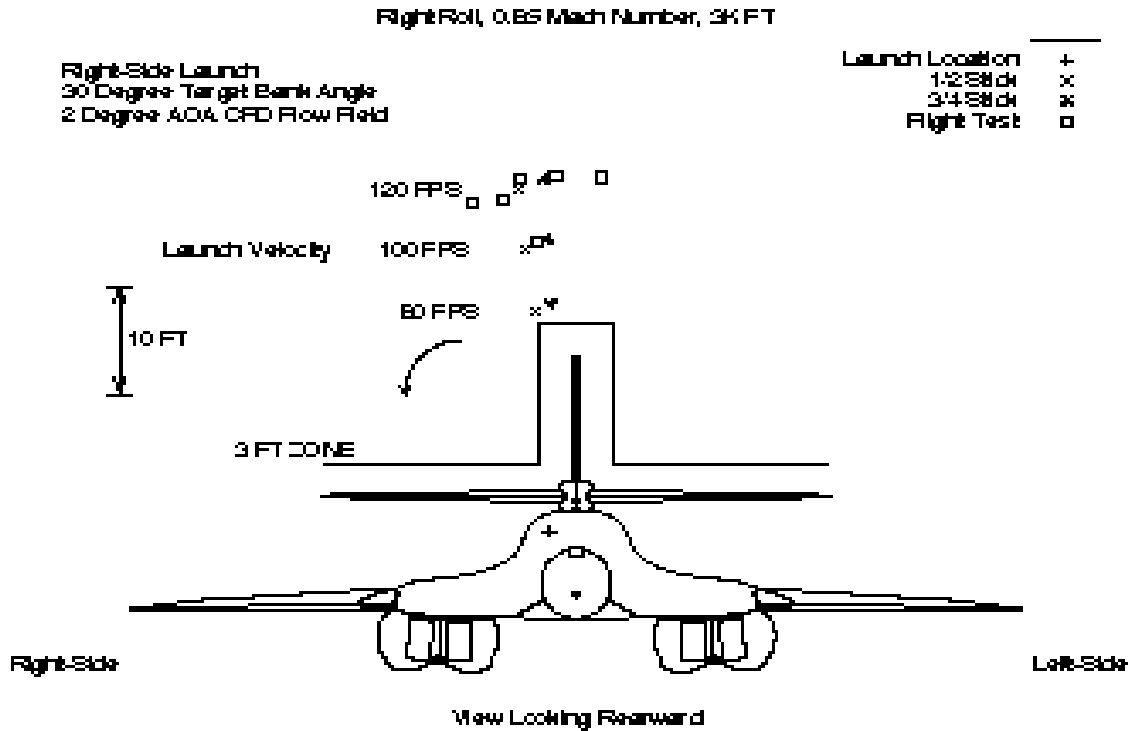


Figure 8: Comparison of Flight-test Data with Computational Model for a Rolling Aircraft Maneuver

In particular, the algorithm would use the time-dependent flight parameters (e.g., angle-of-attack, sideslip, roll rate, and normal acceleration) to “bend” the vectors of the constant angle-of-attack aircraft flowfield. These two tools, employed with standard engineering methods and “rolling” aircraft data from the Rockwell’s B-1B simulator, allowed the AEDC team to successfully model the flares during the rolling maneuvers prescribed in the flight-test plan.

The model predictions for 40 and 60 degrees/second roll rates were validated by the CTF during the flight-test (see Figure 8). These analyses indicated that the flares could strike the tail of the aircraft for any flight condition above 0.85 M when the flare ejection velocity was 80-fps (i.e., the bottom of the ejection velocity spec). At 100-fps ejection

velocity, the analysis indicated that B-1B tactical maneuvers did not cause the flare pellet to strike the tail, even at negative angles-of-attack (negative angle-of-attack “pushed” the tail up toward the trajectory of the flare). This result was depicted as a “hurdle” which the flare could clear, regardless of roll rate or sideslip, at the worst-case negative angle-of-attack (see Figure 9).¹⁸

Another important part of the analysis effort was to consider the flare ejection velocities from lot acceptance testing data provided by Tracor. This part would allow the team to determine if the 80-fps flare was a practical threat. The existing velocity data, consisting of 168 flare ejection tests, reflected a normal distribution and could be analyzed using “textbook” statistical procedures.¹⁹ This provided the important insight that an 80-fps ejection velocity was three standard deviations below the mean. This meant that the chance of an 80-fps ejection was about one in one thousand. The average ejection velocity was slightly more than 100-fps.

The contributions of the modeling effort were evident throughout the test process. With validated models, AEDC could then apply the Taylor-series expansion model to generate solutions quickly for the point at which the flare passed the plane of the vertical tail.²⁰ These solutions were then used to create the safe training envelope required by Air Combat Command (see Appendix A).²¹ The validation of the Taylor series solutions came from the AEDC CFD model and flight-test data. Note that the terms “Safe” and

Note

¹⁸ Arnold Engineering Development Center, *B-1B Flare Strike Investigation*, In-house production, 22 min., 1996. videocassette.

¹⁹ Lawrence L. Lapin, *Quantitative Methods*, 3rd ed. (San Diego: Harcourt Brace Jovanovich, 1985), 62-65.

²⁰ Air Force Instruction (AFI) 16-1001. *Verification, Validation, and Accreditation (VV&A)*, 1 June 1996.

“Unsafe” in the results depicted in Appendix A refer to whether or not the flare would penetrate the 3-foot box that was established by OC-ALC as the desired safety margin. In the case of the 0.95 Mach envelope, for example, all flares cleared the top of the tail, but the “hurdle” was less than 3 feet above the top of the tail.

With the modeling validated by flight-test data, the team made several conclusions. First, the team recommended that ACC/DO expedite the replacement of ejection cartridges to ensure the 100-fps minimum ejection velocity flares entered service. Until that point, all flare deployments above 0.85 Mach should be restricted to straight and level flight. Second, after the new flares and cartridges were installed, the team recommended that all restrictions be removed. The team stressed that the minor damage would continue until the new flare design, which minimized the use of metal sub-assemblies, could be fielded. Even at that point, there could be no guarantee that the fleet would not see an occasional “dud” flare (i.e., one that failed to reach minimum specification ejection velocity).

Notes

²¹ Mr. Neal Brune, Tracor Corporation, to B-1B Sustainment Office, letter, subject: MJU-23B Defensive Flare Technical Specifications, 1 November 1996.

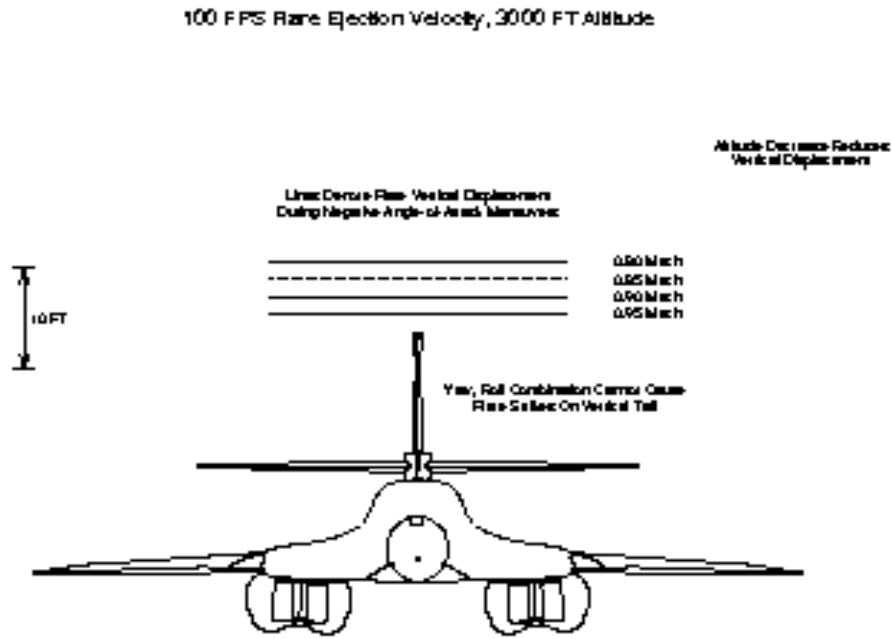


Figure 9: Vertical Displacement for Flare with 100-fps Ejection Velocity during Negative Angle-of-Attack Maneuvers

Evaluating M&S for Flight-Testing Physical Components

In this case, M&S allowed the test team to solve a very difficult engineering problem at the physical component level. The flare strikes were also a hazard to flight safety. Without the predictive power of M&S technology, the test team would have been forced to fly many test points looking for a seemingly “random” flare strike in order to begin looking for a solution. Even after determining the general flight conditions where flare strikes might happen, it would be impossible to develop a solution without taking a statistically significant sample of low flare ejection velocities at the appropriate conditions.

Therefore, statistically significant samples of two events would have been required. First, flight-testers must find the maneuvering flight conditions that “push” the

empennage closer to the flare trajectory. Second, a statistically significant sample of low ejection velocities was required in order to assess the risks of a flare strike.

This approach would have required many high risk flight-test sorties to achieve the same engineering results that six low risk flight-test sorties accomplished with the benefit of M&S technology. In this case, a cost-benefit analysis is straightforward. The B-1B costs \$35,000 per hour to flight-test. The flare strike program required twenty hours of flight-time for a total cost of \$700,000. The M&S effort cost the Air Force less than \$200,000. Total program costs were \$950,000 with including program and miscellaneous management costs figured in. Without the benefit of M&S technologies, at least one hundred B-1B flight-test hours would have been required to get the same results. This would have resulted in \$3.5 million in program costs and taken more than a year to fly. Therefore, M&S was a highly cost effective tool for modeling physical components.

The second criterion for evaluating M&S is engineering validity. Fortunately, the flight-test instrumentation that was especially designed for this project was extremely accurate. The combination of cameras in the flare canisters and the ATIMS III on the chase aircraft allowed engineers to determine the flare position within ± 1 foot along its trajectory. This served as “truth” data for judging the engineering validity of the CFD and Taylor series models of the trajectories. In this case, every CFD solution and corresponding flight-test data point were within 2 feet of one another. The M&S results were valid and sufficiently accurate to provide ACC with the safe training envelope.

The last criterion for evaluating the M&S effort on the flare strike program is comprehensiveness. At the component level, the model was comprehensive. There were

no surprises during flight-test, because flight-test data matched the M&S predictions so well. There were no anomalies or unexpected results.

M&S solutions did not replace flight-test. Instead, M&S allowed flight-testers to attack more difficult problems. Also, M&S greatly enhanced the engineering analysis of flight-test data. M&S methods were cost effective, valid, and comprehensive. Ultimately, the flight-test results from this program were afforded only through the strengths of M&S tools and the computational techniques required to run them. M&S were also essential to the engineering flare redesign effort and getting the fleet back to full operational status. These are rich dividends for small investments in M&S capabilities!

Chapter 3

Case Study Two - Control Systems Modeling with the Variable Stability In-Flight Test Aircraft

We should never test without simulating first.

Honorable Paul Kaminski
Undersecretary of Defense

Introduction: Why do simulations in-flight?

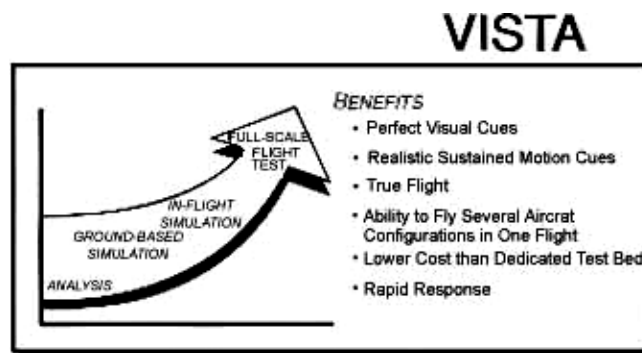
In-flight simulation has proven to be a useful, cost-effective tool that allows test pilots to go beyond the limited capabilities of ground-based simulations and into the actual flight environment. An in-flight simulator is an aircraft that can simulate the handling qualities and flying characteristics of another aircraft in-flight. Aircraft designed to serve as in-flight simulators use especially designed aerodynamic controls along with accurate model-following control input systems to permit the in-flight simulation aircraft to produce motions that duplicate the responses of another aircraft in-flight.

The in-flight simulator uses standard M&S techniques to predict the responses of the simulated aircraft—just like a ground-based simulator. However unlike ground-based simulators, an in-flight simulator has total control over all six degrees-of-freedom for a rigid body. Therefore, an in-flight simulation produces the complete kinesthetic and visual environment of flight rather than the limited and synthetic cues of a ground simulation. Because the variable stability in-flight simulator aircraft—also known as the

VISTA—is an actual aircraft, it provides a degree of realism not present in ground simulation. The pilot experiences the real flight motions, accelerations, and handling qualities of the simulated aircraft, in actual flight conditions. This realism gives the pilot a higher level of confidence in the simulation results.

In addition to the important advantages of providing more realistic environment, in-flight simulation provides the Air Force with an extraordinarily flexible tool to help reduce the cost and schedule of developmental test and engineering work. Indeed, the two most important advantages of in-flight simulation are that it lowers both the costs and risks of testing flight control systems. (see Figure 10)

In-flight simulation also offers greater flight test efficiency and flexibility. Because the simulation is controlled by software that can be modified or changed in-flight, the flight-test team has the ability to fly several simulations using one airframe and one sortie. The in-flight simulator also has the advantage of being easily modified for future growth. By simply changing the flight simulation computers and software, the system is easy to upgrade.²²



Note

²² Philip A. Reynolds, *VISTA/F-16 Design Analysis Report*, CAL-7693-7 (Wright-Patterson AFB, OH.: Air Force Material Command, 24 January 1990),15.

In-flight simulation also allows engineers to gather the data necessary to make scientific predictions of aircraft systems performance. Because VISTA simulations are software driven, hardware prototypes are not required. A prototype aircraft can be extraordinarily expensive to build and modify, and the loss of a single prototype could put an Air Force acquisition program years behind schedule. The Air Force simply cannot afford to risk a prototype aircraft in order to troubleshoot aircraft systems and software when an in-flight simulation can do the job less expensively and more safely.

Historical Background of the VISTA

The original in-flight simulator—the venerable NT-33—was a T-33 airframe fitted an analog variable stability system and a rudimentary variable feel control system. It was upgraded many times and served the Air Force well from 1965 to 1995. During its long and distinguished career, the NT-33 provided important flying qualities data and response information for many newer aircraft. In fact, the NT-33 was used to develop and refine the Air Force’s first fly-by-wire control system on the F-16.²³ Additionally, Mil-Std 1797A *Flying Qualities of Piloted Aircraft*, is filled with data collected by in-flight simulation in the NT-33 aircraft.

The VISTA or Variable Stability In-flight Simulator Test Aircraft was designed to

Figure 10: Benefits of In-flight Simulation
(courtesy of CALSPAN Corp.)

Note

²³ Major Robert A. Wilson and Mr. Karl T. Hutchinson, "What is VISTA? An Introduction to Variable Stability In-Flight Simulator Test Aircraft," *Proceeding of the 38th Annual Symposium of the Society of Experimental Test Pilots*, 1 September 1994, 78.

replace the aging variable stability NT-33. Because of the void created by the retirement of the NT-33, the Air Force tasked Calspan Corporation, the previous operators of the NT-33, to define the requirements for the next generation, high performance in-flight simulator. Calspan identified four specific requirements, which were validated by Air Force Materiel Command:²⁴

1. The airplane must be a two-seat fighter type aircraft with variable feel controls and programmable displays in the front cockpit and all pilot-in-command functions in the rear cockpit.
2. The Variable Stability System (VSS) must be capable of all attitude model-following control and response feedback simulations.
3. The aircraft should have control of six degree-of-freedom forces and moments to satisfy mission and simulation fidelity requirements.
4. It should be relatively inexpensive to operate.

In order to meet these requirements, a modern fighter type aircraft would be required to meet the simulation and performance specifications. Additionally, the aircraft chosen to become the next generation in-flight simulator should be easy to retrofit with a fly-by-wire variable stability control system. Finally, cost was a major program concern. Both the Air Force and Calspan Corporation hoped to use an aircraft that was already in the inventory.²⁵

Several fighter type aircraft were considered, but the F-16D was considered the most suitable because the digital flight control system on the production aircraft was most the

Note

²⁴ Ibid. 79.

²⁵ Program Management Directive for Variable Stability In-Flight Test Aircraft (VISTA), 21 March 1991.

easily retrofitted for variable stability control system.²⁶ Headquarters Air Combat Command and Headquarters Air Force supported this decision by assigning a production F-16D to the in-flight simulator program at no cost to the program.²⁷ Air Force Materiel Command approved Calspan's engineering proposals and Wright Laboratories awarded the modification contract shortly thereafter.

VISTA Aircraft Description

The VISTA was a Block 30 F-16D with the Israeli Peace Marble II dorsal spine. The dorsal spine was added to the basic aircraft configuration to house the computers used by the variable stability system and the aircraft's data recording system. The airplane was equipped with a digital flight control computer and was powered by a General Electric F110-100 engine. The addition of a Variable Stability System (VSS) gives the airplane its in-flight simulation capability. Extensive cockpit modifications were made to place the pilot in the command station in the rear cockpit. Additionally, an airborne test instrumentation system (ATIS) was installed providing on-board data recording and real time telemetry capability.

Sideslip sensors— called beta cones—similar to production F-16 angle of attack cones were mounted on the top and bottom of the forward fuselage. A flight test nose boom was also installed for the developmental test program to calibrate the pitot-static

Note

²⁶ David M. North, "VISTA Primed for Research, Training," *Aviation Week and Space Technology* 142 no. 10 (Mar 6, 1995): 54-56.

²⁷ Wilson and Hutchinson, 80.

system of the aircraft. Several other internal modifications were made to support the additional demands made by the variable stability flight control system.²⁸

These changes included the addition of F-16XL 51-gallon per minute hydraulic pumps instead of the standard 42 gallons per minute pumps and the removal of hydraulic flow restrictors in the servo-actuators for the flaperons and horizontal tails.²⁹ The primary purpose of the hydraulic modifications was to increase hydraulic system capacity to support the rapid control actuations required for in-flight simulation. A more robust hydraulic system also allowed for future upgrades to the variable stability control system.

Perhaps contrasting the two cockpits in the VISTA with a production F-16D best illustrates the uniqueness of the VISTA aircraft. The most obvious change to the front cockpit was the addition of a movable variable-feel center stick. In order to make room for the center stick, the primary flight instruments in the front cockpit were removed. All pilot-in-command functions were removed from the front cockpit making the instrument panel look almost exactly like the rear cockpit of a production F-16D. A removable hard drive similar to a production Data Transfer Unit Cartridge (DTUC) was installed in the front cockpit that interfaced with the variable stability system computers. This hard drive contained as many as 200 pre-programmed flight control configurations and could be removed and replaced in-flight by the front cockpit pilot.³⁰

Another major feature of the front cockpit was the variable feel control system. Stick force and position requirements for the center stick could be changed to simulate various

Note

²⁸ Karl T. Hutchinson, ed., Maintenance Manual for the VISTA/F-16 Variable Stability Aircraft, CAL-7693-10 (Buffalo, NY. January 1992)

²⁹ Wilson and Hutchinson, 81.

³⁰ Karl T. Hutchinson, ed., VISTA/F-16 Variable Stability System Pilots' Operating Manual, CAL-7693-9 (Buffalo, NY. January 1992), 1-38.

aircraft configurations and flight conditions. Because the side stick in the front cockpit was the standard F-16 side stick with only ¼ inch of motion available—only force command configurations were available through the VSS with this stick. The variable feel system could also vary other parameters such as trim pre-loads, breakout, friction, nonlinear force gradients, and bob-weights on the controls. Changes in stick force gradients, friction, and breakout forces could all be independently programmed with the variable feel system.

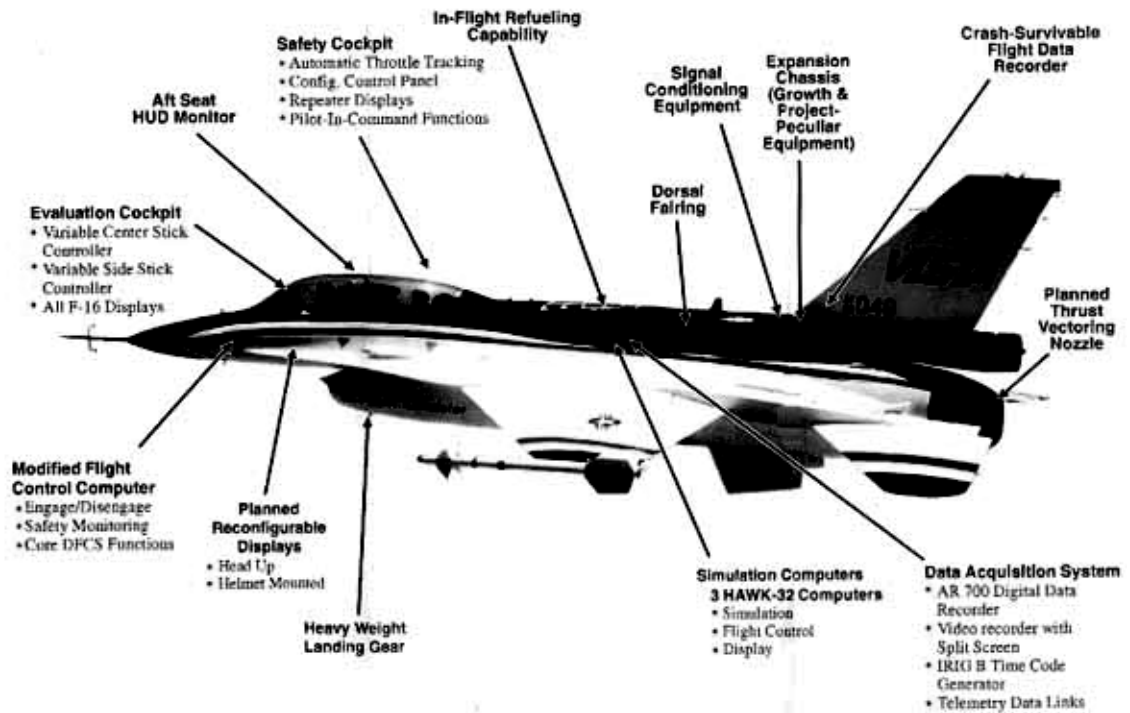
A less obvious change to the front cockpit was that the throttle was not mechanically connected to the rear cockpit throttle or directly to the engine controls. Instead, the throttle in the front cockpit of the VISTA worked entirely through the variable stability system.³¹ Because the throttle was not mechanically connected to the engine and the fuel shutoff switch had been removed, the engine could not be started or shut down from the front cockpit.

The rear cockpit was very similar to the appearance and function of the front seat of a production F-16. All pilot-in-command functions were relocated from the front to the rear cockpit—including engine start and shut down controls. The front and rear throttles were not mechanically connected. This design feature allowed the engine to be used as part of the simulation. When the VSS was engaged, the computers monitored the front cockpit throttle position and commanded engine response according to simulation requirements. Although the rear cockpit throttle did not send inputs to the engine with the VSS engaged, the rear cockpit throttle position was driven by a servo to match the VSS engine command. This minimized thrust transients when the VSS was disengaged.

Note

³¹ *ibid.* 1-56.

VISTA



(courtesy of CALSPAN Corp.)

Figure 11: The VISTA Aircraft

Modeling and Simulation Methods

VISTA Variable Stability System

The Variable Stability System (VSS) in the VISTA aircraft provided limited six degrees of freedom simulation capabilities. The system commanded symmetric and asymmetric horizontal tail movements, symmetric and asymmetric flaperon movements, rudder movements, and throttle control. The only surfaces not controlled by the VSS were the leading edge flaps and speedbrakes. The flaperons could be positioned

symmetrically both trailing edge up and trailing edge down to provide direct lift control.³² The brains of the VSS system were three flight control computers salvaged from Hawk missile systems that calculated aircraft control surface actuation necessary to perform the in-flight simulation. An additional flight control computer from a Titan missile performed the function of controlling the variable feel system on the center stick.³³

The rear cockpit of the VISTA did not incorporate the VSS flight controls and was always configured as a production F-16D aircraft. The rear cockpit only had the standard F-16 side stick controller and used the production software to drive the flight controls exclusively. The F-16 flight control computers and software were isolated from the VSS system. The VSS was also designed to degrade gracefully to the F-16D production flight control laws. However, the control panel in the rear cockpit could manually “lock-out” the VSS signals to the control surfaces in case of an emergency.³⁴

The VSS in the front cockpit of the VISTA was functional in one of three separate modes: variable stability, F-16 emergency mode, and F-16 convenience. A major point for the flight crew to remember is that in order to preserve the simulation algorithms used for variable stability, only one cockpit could be active at a time when the VSS was driving the flight controls.³⁵ When the rear cockpit pilot was flying, the front cockpit controls were inoperative and vice versa when the front cockpit was flying, the rear cockpit controls were inoperable. The only time both cockpits are active simultaneously is when the backup emergency mode is used. This backup mode is simply an independent

Note

³² Wilson and Hutchinson, 81.

³³ *ibid.* 82.

³⁴ Karl T. Hutchinson, ed., VISTA/F-16 Variable Stability System Pilots’ Operating Manual, CAL-7693-9 (Buffalo, NY. January 1992), 3-10.

³⁵ *ibid.* 2-15.

flight control system that uses normal production F-16D flight control computers and software. This independent back-up system is available in case of a VSS malfunction. It provides a way for the front seat pilot to fly without the VSS in an emergency and cannot interfere with the normal flight control system. This provided another layer of redundancy and safety in case of computer malfunctions.

The variable stability system was used for all simulation work. The F-16 emergency mode did allow the front cockpit pilot to fly the aircraft using the side stick and normal F-16 control laws through the VSS. This also allows the front seat pilot an emergency means to recover the aircraft should the rear cockpit safety pilot be unable to do so. The F-16 convenience mode is very similar to the emergency mode. Convenience allows the front seat pilot to fly the aircraft while the rear seat pilot tends to other duties such as reprogramming the VSS computers or recording flight test data. The main difference between convenience and emergency mode is that in convenience, all manual safety trips that revert control to the rear cockpit are still available and the rear cockpit pilot maintains throttle control if desired. Figure 12 below summarizes the various flight control modes.

VISTA Flight Control Modes

Front Cockpit	Rear Cockpit
Variable Stability	Always F-16 flying qualities
F-16 Emergency	
F-16 Convenience	

Notes: Only one cockpit may be active at a time. The back up emergency mode is separate from the VSS and provides a redundant flight control system.
--

Figure 12: Flight Control Modes

Engineering Results Flight-Testing Robust Flight Controls for the F-22

All aircraft depend on their flight control systems for safe, satisfactory operation. Assuring stability, trim, and performance with all components functioning properly is the primary design goal. Stability, trim, and performance must also be maintained following digital system failures. Digital fly-by-wire flight control failures also have entirely different failure characteristics than mechanical flight control systems. Although computer software seldom fails, it is susceptible to latent programming faults that may surface unexpectedly and may be hard to detect. Unfortunately, these failures are seldom subtle or graceful. Multiple failures can also occur, particularly because of physical damage. While not strictly systems failures—pilot error, power transients, and meteorological hazards—can produce system states that require prompt responses.³⁶ Therefore, control system logic must do more than just accommodate isolated single-point failures. The VISTA research aircraft was designed to allow control systems engineers the resources adequate for modeling flight control systems under these conditions.

Failure-tolerant control systems can be characterized as robust, reconfigurable, or some combination of the two. A system that retains satisfactory performance in the presence of input parameter variations or component failures is called robust. If the

control system's structure or parameters alter in response to system failure, it is reconfigurable. In the case of reconfigurable control systems, the control system detects, identifies, and isolates failures, and then it modifies control laws as required to maintain acceptable stability, trim, and performance.

Early VISTA research focused on methods of designing robust flight control systems for the F-22 that compensate for potentially catastrophic failures of aircraft systems—especially during combat. Robust flight control methods are usually based on redundant systems, “expert systems”, and probabilistic evaluations of control responses. The F-22 program plans to eventually incorporate “expert systems” into the aircraft control system, but initially it will rely on redundancy and probabilistic evaluations.³⁷ Probabilistic data also helps predict the effects of system failures on man-in-the-loop stability and performance through assessment of commonly accepted design criteria outlined in Mil-Std 1797A *Flying Qualities for Piloted Aircraft*.

VISTA simulations of control systems designs determined the likelihood of system responses and whether the proposed F-22 control systems responses fell within Mil-Std 1797A guidelines. This research was a major step toward computerized design of digital flight control systems. The computerized design can eventually be incorporated into a larger digitized aircraft design processes such as the one used to design the Boeing 777 described in the next chapter.

The principal functions of the F-22 failure tolerant flight control system are failure detection through built-in-test alarms, off-nominal operations, component failure

Notes

³⁶ Robert F. Stengel, "Failure-Tolerant Flight Control Systems" FAA Grant No. 95-G-022, 24 July 1997, n.p.; on-line, Internet, available from <http://www.princeton.edu/~stengel/FTFCS.html>.

identification, and control-system reconfiguration. Detection and identification are combined in the built-in test functions. Although in-line monitors provide direct and rapid response to specific failures, it is impossible to provide full coverage of all failures by instrumentation, which is also subject to failure. However, a practical failure detection, identification, and reconfiguration (FDIR) solution could be found by using M&S technologies. The F-22 flight control system compares expected response from the VISTA data to the actual F-22 response, inferring component failures from the differences and changing either the configuration of the aircraft or the parameters of the control system.

The F-22 failure detection algorithms are exemplified by a generalized likelihood ratio test, which uses a Kalman filter-like recursive equation to sense discrepancies in the system response.³⁸ This test compares the probability of the estimator's actual measurement residual with its expected value, detecting a jump or discontinuity that indicates a possible failure. Because variations in the measurement residuals were extensively tested in the VISTA, these indicators are very accurate and sensitive to off nominal performance. The F-22 FDIR system is very sensitive to off-nominal performance and failures are easy to detect. However, the VISTA tests did not produce precise indications of the specific failed components. Modeling errors still occasionally hamper detection.³⁹

The crash of an F-22 during flight test due to a control system failure also reminds us that further improvement in the design of the F-22's digital flight control systems is

Notes

³⁷ Charles W. Brown, Lockheed Corp., interviewed by author, 7 March 1998.

³⁸ 416 Flight Test Squadron, "F-22 Software Failure, Detection, Identification, and Reconfiguration (FDIR) Test Plan," Edwards AFB, CA. Jun 1996. 38.

warranted. In this case, the cause of the failure was determined to be missing computer code in flight control system. Because the software is modified occasionally throughout the lifetime of the aircraft, there is a continuing need to assess and prevent potentially catastrophic accidents as the result of control system failures. The VISTA allowed engineers to flight-test changes to the control systems software used in the F-22. In-flight simulation permitted the Air Force to assess the F-22 fly-by-wire control systems conveniently and safely.

The F-22 uses models developed during the VISTA flight-tests to reconfigure flight controls in order to retain nominal stability, performance, and trim characteristics. However, there is a tradeoff between speed of reconfiguration, computer storage requirements, and flexibility of reaction. Models and parameters for all conceivable failed states could be generated off-line and stored for eventual use. However, this approach would require an enormous amount of memory. Conversely, adaptation requires minimal data storage and theoretically could adjust to unanticipated failures, but design algorithms must be executed and their results accepted soon enough to provide sufficient failure tolerance.⁴⁰ Because the aircraft is open-loop-unstable, higher control activity combined with the control saturation limits reduce the solution space within which closed-loop stability can be assured.

Notes

³⁹ Fred Carmody, Lockheed Corp., interviewed by the author, 1 April 98.

⁴⁰ Robert F. Stengel, "Failure-Tolerant Flight Control Systems" FAA Grant No. 95-G-022, 24 July 1997, n.p.; on-line, Internet, available from <http://www.princeton.edu/~stengel/FTFCS.html>.

Evaluating M&S for Flight-Testing Closed-Loop Control Systems

M&S provide an important method for evaluating the flying qualities of aircraft without putting an expensive prototype aircraft at risk. The F-22 costs the Air Force at least \$20,000 per hour to flight-test. The VISTA costs \$6,000 to \$8,000 per flight hour, depending on the specific software and instrumentation requirements.⁴¹ The VISTA also has the ability to change programs in the VSS system in-flight. Therefore, the flight-test team has the ability to fly several simulations using one airframe and one sortie.

The Air Force has already lost one F-22 to flight-control problems. The crash resulted in the loss of an \$83 million asset and put the program behind schedule. Fortunately, there was no loss of life in this accident. Nevertheless, this mishap is an important reminder that flight-testing flight control systems can be very dangerous. In this case, the cost-benefit analysis is straightforward. It is cheaper and safer to flight-test in the VISTA than in the F-22.

Digital flight-control systems can be especially dangerous, because software faults are so difficult to detect and can open a feedback control loop on an open-loop-unstable aircraft. As long as the in-flight simulator provides valid engineering data, simulation is preferable to flight-testing with an F-22. The data provided by the VISTA was crucial to designing robust flight controls for the F-22. The role software plays in determining the airworthiness of a control system design cannot be overemphasized. Small changes to software can drive large changes to the flight control actuators and adversely affect the aircraft's flying qualities.

Note

⁴¹ These figures are the best available estimates as of 1 May 1998 from the AFFTC resources branch.

In-flight simulation is an important capability. If the analysis of aircraft dynamics is poor on the ground, the actual aircraft dynamic response is likely to be even worse in flight. A corollary to this lies at the core of the VISTA's mission. Even if the computed aircraft dynamics and flying qualities are very good on the ground—such as the F-22—the handling qualities are not necessarily good in the air.

The only way to compare computed dynamic responses with actual aircraft response is by flight-test. In-flight simulation is the only way to flight-test digital control systems safely. VISTA's probabilistic models of the F-22 flight parameters and control responses matched the F-22 data almost exactly—within the flight envelope of the VISTA.⁴² Therefore, the engineering validity of the VISTA data was excellent, but the VISTA could not provide a comprehensive model data because of its limited flight envelope.

Although the engineering data provided by the VISTA was excellent, the VISTA did not have as large a performance envelope as the F-22. Therefore, the VISTA model was not comprehensive. The VISTA could only model a subset of the actual F-22 responses. At high Mach numbers, the VISTA could not provide modeling data because the aircraft is limited to 1.6 mach although the F-22 can attain 2.0 mach number. Likewise at high altitudes, the VISTA could not simulate certain super-cruise conditions because of engine limitation on the VISTA's engine that prevented the initiation of afterburner above approximately 38,000 feet.⁴³

Fortunately, the limitations of the VISTA were known by the flight-test team. Therefore, the VISTA model of the F-22 control system was simply a subset of the actual

Note

⁴² Wilson and Hutchinson, 81.

⁴³ Karl T. Hutchinson, ed., VISTA/F-16 Variable Stability System Pilots' Operating Manual, CAL-7693-9 (Buffalo, NY. January 1992), 5-3.

F-22 control responses. Although the model was not comprehensive, no errors of omission were made interpreting the VISTA data, and the F-22 did not have unexpected control responses.

Because the Air Force already has extensive experience with in-flight simulation, many of the lessons learned during the development of the F-22 flight control system are lessons relearned and reinforced from the earlier experience with in-flight simulator programs. The VISTA provides a cost-effective and valid model, but not necessarily a comprehensive one. In-flight simulation is already an integral part of designing the flight control system for a digital fly-by-wire aircraft. Very soon, in-flight simulation will become part of an overall digitized aircraft design process, such as the Boeing 777 case described in the next chapter. In-flight simulation is the only way to safely flight-test digital flight-control systems. The Air Force should continue to promote and use this important M&S technology.

Chapter 4

Case Study Three- Modeling Complex Systems by Designing the Boeing 777 in Cyberspace

Modeling and simulation will improve readiness and reduce costs for the nation because it will allow us to demonstrate the flexibility, responsiveness, and utility of airpower...

General Ronald R. Fogelman
USAF Chief of Staff

Introduction

The previous case studies demonstrated how the capabilities and limitations of M&S vary as models increase in scope and complexity from the physical component level to closed-loop control systems. The B-777 case increases the scope and complexity of the modeling effort by modeling a complex system with human interactions. Recent advances in M&S technologies have made significant changes in the way the Boeing Aircraft Company designs, builds, and tests airplanes. The Boeing 777 (B-777) was the first aircraft created using M&S methodologies as the foundation of their design and engineering processes. The changes wrought by M&S were very dramatic and encompassed many areas, including technical, organizational and administrative changes. Consequently, Boeing has touted the B-777 as more than just a product, but rather a new

process for the company.⁴⁴ Although the technical innovations were impressive, what made the B-777 project unique was the way that Boeing integrated state of the art M&S technologies throughout the design, production, and testing of the aircraft.

Historical Background of the B-777 Program

In the early 1990s, Boeing was beginning the concept development for its next generation commercial airliner. The company was losing its market share for commercial airliners to the Airbus consortium in Europe and US air carriers were finding the advanced technology incorporated into the Airbus 320 very attractive for the US domestic market. Because the Airbus consortium enjoys financial backing from European governments, Boeing was under intense pressure to reduce its operating costs in order to be financially competitive. Nevertheless, both the aircraft and the production methods needed to be state of the art in order for Boeing to be technologically competitive. M&S was the key technology that enabled the B-777 program to meet both imperatives. M&S reduced costs and eliminated the costly mockup and prototyping stages of the aircraft design process.

Designing and building a new commercial jet airliner is a long process, sometimes lasting five to ten years. The process is relatively infrequent and expensive as well. The Boeing Company could only expect to go through the process of designing and building a new airliner once or twice per decade. Therefore, senior Boeing management believed that it was critical to document the new M&S design and production innovations for

Note

⁴⁴ Shad H Shokralla, "21st Century Jet, The Boeing 777," *National Engineering Education Delivery System* 26 January 1997, n.p.; on-line, Internet, 1 June 1998, available from <http://www1.needs.org/develop/b777>.

future projects.⁴⁵ This was especially true for the B-777 program because of the many technological “firsts.” Fortunately, M&S technologies enhanced the documentation of the design process due to the relatively inexpensive storage and archival of computer data. Computer Aided Design (CAD) also enhanced the design process because it was easier and faster to learn than traditional engineering drawing methods. Over the course of the B-777 program, the computer models became a part of Boeing’s “corporate memory.” The models will undoubtedly continue to play an important part in future aircraft design programs.

However, when modeling a complex system and trying to account for human interaction with that system, M&S methods currently have significant limitations. Boeing pushed the state of the art in M&S for the B-777 program and ran up against some of these limitations. The B-777 program made significant engineering oversights and errors of omission. The company also had managerial difficulties because of the self-imposed dependence on computer technology. Ultimately, M&S could not do it all on a project as complex as the B-777. However, M&S was an extraordinarily valuable tool, and the decision to use M&S methods turned out to be a successful solution for the company despite the difficulties and occasional oversights.

The Modeled System Boeing 777 Aircraft Description

In order to understand the process of using M&S on a major program, it is important to know the product. In this case, the product is a new jet airliner with numerous technical innovations. The B-777 is the biggest twin-engine aircraft ever to fly. The B-

Note

⁴⁵ John E. Cashman, "Progress to the Plan," *Proceeding of the 39th Annual Symposium of the Society of Experimental Test Pilots*, 1 September 1995, 7.

777 wing span is almost 200 feet—equal to the Boeing 747’s wingspan. The B-777’s nacelle is twelve feet in diameter, which is approximately the diameter of a Boeing 757 fuselage. The B-777-200 is also the first twin-engine aircraft to have a range of 4,000 to 8,500 nautical miles carrying between 300 and 400 passengers. The aircraft was classified as a very heavy or jumbo-jet, which places it in the 500,000 to 660,000 lb. weight class. The initial model of the B-777 flies 375 passengers 4,630 nautical miles. An increased gross weight model will carry 305 passengers 7,230 nautical miles. This is the preferred configuration for long, intercontinental routes. Future members of the B-777 family will carry as many as 550 passengers and fly farther than the current 747-400 model. The aircraft entered commercial service in June 1995, and it has been certified for extended-range twin-engine operations (ETOPS). Additional technical information about the aircraft is located at Appendix C.⁴⁶

During the design definition stage of the B-777, many new technologies were investigated and discussed with the airlines. According to Boeing’s Vice-President for the B-777 project, Phil Condit:⁴⁷

“ The decider in this area was to select only the technologies that “bought” their way onto the airplane. That is the technologies that would provide an economic or safety return to the airline, as well as ones they were currently ready to incorporate into their internal systems. We are also attempting to build a system that could be upgraded for other known and future digital technologies such as an electronic library system for on-board technical information, differential GPS, and HUD to cite a few.”

Among the new technologies to make the “cut” onto the airplane design were a digital avionics suite, high-speed data buses, centralized Airplane Information

Note

⁴⁶ *ibid.* 7.

⁴⁷ Shad H Shokralla, "21st Century Jet, The Boeing 777," *National Engineering Delivery System* 26 January 1997, n.p.; on-line, Internet, 1 June 1998, available from <http://www1.needs.org/develop/b777>.

Management System (AIMS), LCD flat panel displays, and a new generation of high bypass-ratio/high-thrust engines.⁴⁸

The B-777 also used an advanced fly-by-wire flight control system. Essentially, fly-by-wire technology is a system of transmitting flight control commands from the cockpit via data cables to actuators on the control surfaces. Primary flight control computers convert the pilot's movement of the control column and rudder pedals into movements of the aerodynamic control surfaces via input-response models stored in the computer memory. This means that there are no direct links—either mechanical or hydraulic—between the pilots and the control surfaces. The computers also determine the force and displacement necessary at the control column and rudder pedals to provide an artificial feel system for the flight crew. Fly-by-wire systems eliminate weight and reduce control system complexity by removing a majority of the cables, linkages, and hydraulic tubing. Furthermore, since computer models drive the control actuators from pilot inputs, the aircraft's flying qualities can be fine-tuned with software changes for safer and smoother aircraft control.⁴⁹

Fly-by-wire is not a new technology. It has been used in military aircraft for years. The F-16 was the first production aircraft to use fly-by-wire technology with an analog system introduced in the late 1970s. The Airbus consortium has also used a hybrid analog/digital fly-by-wire system in the Airbus 320 since 1985. The Airbus 320 uses a two-axis digital system in which the yaw controls were analog. However, the B-777 was the first commercial aircraft to incorporate a completely digital three-axis fly-by-wire

Note

⁴⁸ Cashman, 10.

⁴⁹ Jan Roskam, *Airplane Flight Dynamics and Automatic Flight Controls* (Lawrence KS: Design, analysis, and Research Corporation., 1994), 183-186.

system. The Boeing system was also the first production fly-by-wire control system that blended inputs to the flight control software.⁵⁰ This ability to smoothly blend control inputs is similar to the VISTA in-flight simulator discussed in the previous case. The B-777 fly-by-wire system typically used a blend of normal aircraft acceleration, airspeed, and pitch rate to model and compute aircraft response to pilot inputs. This technique of blending inputs to the flight control laws as part of a control-response model in the flight control computers resulted in significantly improved handling qualities over previous fly-by-wire systems.

Innovative Design Techniques

In the past, Boeing had always made thousands of engineering drawings and then built a full-scale non-flying mockup of the aircraft to check fit and interference problems. In the case of the B-777, the cost of the mockup alone was estimated to have been at least \$22.5 million.⁵¹ Without M&S technologies and the computer design network, all the various aircraft systems must be designed independently.

Therefore, effective systems integration required a physical mockup before the aircraft could enter production. For example, the physical mockup made sure that a bolt did not occupy the same physical space as a hydraulic line, or that an electrical conduit did not run across the middle of a ventilation duct. The mockup was also used to check accessibility of all the parts for maintenance work.

Note

⁵⁰ Cashman, 6.

⁵¹ Shad H Shokralla, "21st Century Jet, The Boeing 777," *National Engineering Delivery System* 26 January 1997, n.p.; on-line, Internet, 1 June 1998, available from <http://www1.needs.org/develop/b777>.

However, the B-777 program avoided the necessity of mockups by using computer aided design (CAD) methodologies. CAD replaced the tedious hand drawn layouts and full-size mockups of earlier aircraft designs. Boeing used an innovative combination of networked computer systems, M&S technology, and Design/Build Teams (DBTs) to coordinate design requirements and engineering priorities.

In order to accomplish this coordination at the component level, the B-777 division used a CAD software suite based on CATIA (Computer-Aided, Three-dimensional Interactive Application) and a finite element analysis program known as ELFINI. Both programs were developed by Dassault Systems of France and licensed in the United States through IBM.⁵² CATIA was used for the all the detailed computer design work, as well as the three-dimensional solid modeling. At the aircraft systems level, Boeing designers also used EPIC (Electronic Pre-assembly Integration on CATIA) as well as other digital pre-assembly applications developed by Boeing specifically for the B-777 project.⁵³

In order to model the B-777 as a complex system, Boeing connected 2,200 CATIA workstations into an eight-mainframe computing cluster. This mainframe cluster was also linked to mainframes and CATIA workstations throughout the world. This network required the largest data storage capacity of any computing facility in the world. The B-

Note

⁵² Michael Mecham, "Aerospace Chases the Software Boom," *Aviation Week and Space Technology* Vol. 147 no. 14 (Oct. 6, 1997): 47.

⁵³ Shad H Shokralla, "21st Century Jet, The Boeing 777," *National Engineering Delivery System* 26 January 1997, n.p.; on-line, Internet, 1 June 1998, available from <http://www1.needs.org/develop/b777>.

777 division required over three tera-bytes (3×10^{12}) of data to store all the aircraft design information.⁵⁴

M&S technologies are more than three-dimensional design tools, when dealing with complex systems. CATIA was used as a component level modeling method as well as a digital pre-assembly tool. The DBTs used this data in conjunction with a computer network to produce a "paperless" design that also allowed engineers to simulate the complete assembly of the B-777. By using the three-dimensional solid images generated on a computer, the B-777 airplane could be pre-assembled in cyberspace to position parts properly and to ensure a good fit. Additional software tools allowed for "fly-through" analysis of various hardware configurations. Human factors and maintenance access questions were answered by maneuvering a digital "virtual mechanic" in three-dimensional space (see Figure 13). Many complex systems issues including some human factors and maintenance accessibility studies could be done from individual workstations.⁵⁵ With a three-dimensional database that everyone could use simultaneously, design interference problems were greatly reduced before full-scale production.

Note

⁵⁴ Cashman, 12.

⁵⁵ Shad H Shokralla, "21st Century Jet, The Boeing 777," *National Engineering Delivery System* 26 January 1997, n.p.; on-line, Internet, 1 June 1998, available from <http://www1.needs.org/develop/b777>.



Figure 13: A “virtual” mechanic inspects the landing gear

(courtesy of Boeing Corp.)

Another benefit of M&S technology was that the CATIA system also allowed flight-test instrumentation to be designed into a standard airplane during normal factory production. This resulted in a more efficient design process, and the elimination of even more specialized mockups for test instrumentation. According to Boeing’s Chief of Flight Test Operations, Mr. John Cashman “CAD design methods meant less rework of normal aircraft systems when test instrumentation was installed.”⁵⁶

Modeling & Simulation Methods

Systems Level Modeling and Knowledge Based Engineering

Knowledge Based Engineering (KBE) on the B-777 program also took M&S technologies a step beyond component level models and into systems level modeling

Note

⁵⁶ Christoph W. Klomp, Boeing Corp., interviewed by author, 15 March 1998.

methods. KBE not only captured the design information but also the rules that were used to create the design. KBE is also known as an "expert" system. An "expert" system is a computer programmed to mimic the procedures and decisions that an experts would make. For example, KBE uses data about material expense, strength, and weight to determine if it meets the requirements for a specific part. An "expert" system can make design decisions within a engineering design framework and is useful in a large engineering project because "expert" systems allow the computer model to keep track of multitudinous design rules.

Boeing's KBE system utilized CAD software from Concentra Inc., in conjunction with computer code developed in-house by Boeing.⁵⁷ The KBE software was written in LISP—a common object-oriented computer language favored for expert-system applications. Expert systems using standardized design rules generally lead to more part commonality and reduce manufacturing tooling costs. For example, stringers in a wing are similar structural elements to ribs in a fuselage. However, they were often designed using different criteria based on the experience gained by many designers on the different fuselage and wing design teams. The KBE methods made sure that the lessons learned on one design project were not lost on another. KBE also helped prevent the duplication of effort during engineering design and analysis of similar parts.

However, KBE is not a completely mature modeling methodology and the rules used by "expert" systems sometimes work at cross-purposes. For example, design safety margins vary widely on structural parts. Fuselage stringers along the top of the aircraft must be as much as 50 percent stronger than the stringers on the bottom of the fuselage.

Note

⁵⁷ *ibid.*

However, the engineering drawings are the same for both parts. During the manufacturing process extra metal is carefully machined away from the lower stringers to save weight. An “expert” system must be able to adjust for the different requirements for each part, and then be able to label and track the part through the production phase. KBE worked well for the wing parts but needed a much more comprehensive database for fuselage components. In the case of the B-777, some fuselage parts were over-built because of the inadequate database. Boeing knew the KBE model was still incomplete at the systems level, but decided to continue using it in order to save production time.⁵⁸ However, these errors of omission at the systems level resulted in a significant weight penalty on the final aircraft design.

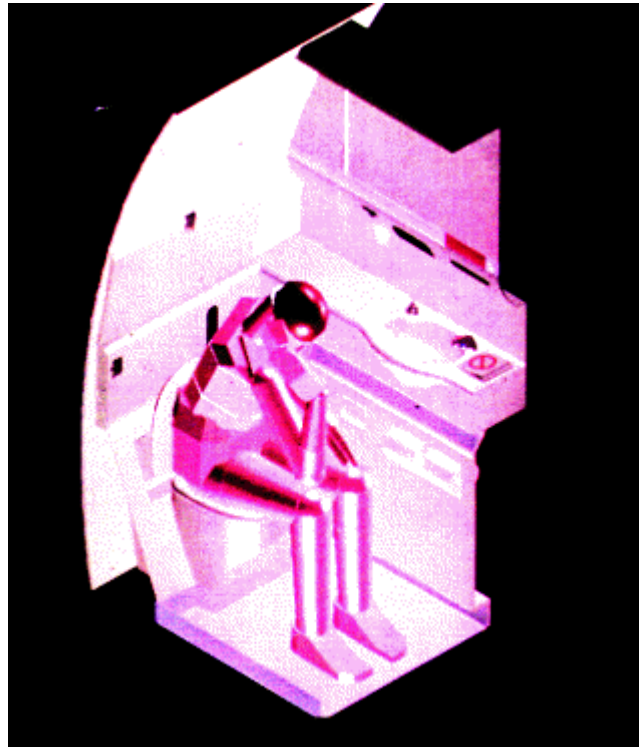
On the other hand, one of the major benefits of KBE was the ability to run computer simulations to optimize design based on KBE logic and conditional rules. This capability allowed designers to conduct additional trade-off studies and look at more options, which resulted in a better design with reduced material and complexity. Standardized manufacturing rules in the system resulted in designs that were easier and cheaper to manufacture. The KBE system also automatically generated parts lists to facilitate production.

KBE was not only used in engineering and structural design but also in customizing each cabin configuration. All the rules for the dimensions and spacing of seats, aisles, lavatories and galleys were entered into the system which allowed each airline to quickly determine

⁵⁸ *ibid.*

Note

the maximum number of seats and locations of all the components for their chosen configuration (see Figure 14). This process helped reduce the time required for configuration changes to approximately three days as opposed to three weeks to a month



without M&S.⁵⁹ As far as the passengers were concerned, this meant is that individual seat selection was now an important issue. The same class seats on the same flight could vary by one to two inches in both legroom and seat width because the computer was

Figure 14: Computer Ponders
making the most efficient use of space—not necessarily the most equitable one.

The FAA requirements for the final stress analysis were also input to the KBE. This meant that FAA requirements were design rules from the beginning. Therefore, critical engineering deficiencies could be found and corrected much earlier than the prototype or

test phase. For example, the maximum landing gear side loads during crosswind landings was an engineering specification. KBE used “expert” system to design the landing gear system, and the model of the complete aircraft prevented the engineering specification from being violated in the final design.⁶⁰ This complete aircraft model was developed using the technique of concurrent engineering.

Complex Systems Modeling and Concurrent Engineering

At the next level of modeling complexity, the complex systems model, Boeing used concurrent engineering methods. Concurrent engineering is the concept of “working together in cyberspace,” and was an integral part of the B-777 design methodology.⁶¹ The basic idea behind concurrent engineering is to take advantage of KBE and networked M&S capabilities. Design and manufacturing teams worked concurrently on the design to decrease later change orders and to increase efficiency in production.

Concurrent engineering was not a new concept or revolutionary idea, but for Boeing it was a completely new way of doing business. According to Boeing’s Vice-President for the B-777 project, Phil Condit “Boeing is a conservative company that dislikes change” and both the manufacturing and design teams were comfortable with traditional engineering and manufacturing methods. The old stovepipe design teams and “throw it over the wall method” technique seemed to work well enough in the past. Stovepipe design methods also gave both design and manufacturing engineers a ready scapegoat for errors. However, this was not an efficient design or production process. Boeing Vice-

Notes

⁵⁹ Shad H Shokralla, “21st Century Jet, The Boeing 777,” *National Engineering Delivery System* 26 January 1997, n.p.; on-line, Internet, 1 June 1998, available from <http://www1.needs.org/develop/b777>.

⁶⁰ Richard W. Schmitt, Boeing Corp., interviewed by author, 17 April 1998.

⁶¹ Christoph W. Klomp, Boeing Corp., interviewed by author, 15 March 1998.

President Phil Condit pointed out that, on average, every drawing in the old Boeing system was changed four and one half times before final release. According to Condit, "Boeing designed four and a half planes for every plane we built."

Concurrent engineering saved a great deal of time by preventing error and rework, but it required heavier emphasis on planning at an earlier stage. This saved many design iterations because the team's product did not have to go from the designer to planner to manufacturer to assembly and back again as everyone uncovered imperfections to the original design in turn. Because all the parties were involved from the beginning, the design did not leave the team without being reviewed by everyone involved.

Prior aircraft development programs suffered from changing requirements and high redesign costs. Design requirements were constantly changing especially as full-scale mockups were built to check form, fit, and function of the individual aircraft components. Redesign meant costly delays not just in the months leading to the first flight, but throughout the flight-test and certification process.

Fortunately, M&S technologies allowed Boeing to overcome many of the difficulties and delays inherent in traditional design practices. The B-777 was the first aircraft ever to be 100 percent digitally designed using three-dimensional solids modeling technology. Because the individual components were stored as three-dimensional computer models, the form, fit, and function of the individual components could be checked with M&S tools at a computer workstation. Throughout the design process, the airplane was "pre-assembled" on the computer workstations, eliminating the need for costly full-scale mockups, saving at least \$22.5 million in program costs.

Because the CATIA workstations were networked, it was also easy to coordinate design changes between the teams. The same M&S techniques used during the design phase also allowed a “virtual” B-777 airplane to be digitally “pre-assembled” in cyberspace. M&S allowed the teams to study the effects of design changes on the aircraft. Design changes could be coordinated digitally before building expensive prototypes and then redesigning for unforeseen changes. Concurrent engineering permitted a more mature and stable design to be reached sooner. Therefore, Boeing decided to set a very aggressive manufacturing and flight-test schedule for the B-777.

The CATIA network performed so well at the engineering component level of M&S that only a nose mockup (to check critical wiring) was built before assembly of the first flight vehicle. The center of the nose mockup was only 0.03 mm out of alignment with the middle of the fuselage as measured on the waterline of the aircraft. This is approximately an order of magnitude improvement over traditional engineering and prototyping methods without CAD design. During initial production, the engineering results of this CAD design work were also quite impressive. For example, the port wing tip of the first B-777 was out of position by approximately one-thousandths of an inch when attached to the fuselage, and the starboard wing was located within the accuracy of the laser theodolites used for alignment. In addition, the body section joints on the first airplane required no shims and the aircraft’s seat tracks lined up to within one-thousandths of an inch over the entire length of the fuselage.

Moving into the production phase, Boeing used M&S technology to minimize production costs and to ensure the B-777 was a service-ready product upon delivery to the airlines. The B-777 program established a number of goals to address this issue. One

of the first program goals was to reduce error and rework in the manufacturing process by 50 percent by using M&S technology and “design/build teams.”

Synthesis of Modeling and Simulation Methods with DBTs

In order to achieve the goal of reducing rework and error, 238 design/build teams (DBTs) made extensive use of CAD, KBE, and concurrent engineering over computer networks so that design changes could be coordinated easily. DBTs usually consisted of approximately fifteen members with representatives from design, manufacturing, quality assurance, customer service, flight operations, and flight deck crewmembers. The DBTs also included over 300 airline employees who came to Boeing in order to make inputs to the program. This was an important organizational change for the Boeing Company. All the parties that could alter the design or affect the schedule were now able to make inputs at the very beginning of the design process instead of waiting for a mockup or prototype.

The typical team met every few weeks to monitor progress and discuss problems. Boeing quickly discovered that dividing people into teams did not assure the success of the DBT concept. Teams must have effective leadership in order to guide the process toward a decision. Many teams were great at discussion but never arrived at engineering solutions. Since the first design entered into the computer system often was the first one to be “chopped” or criticized by the other teams, initial data input was sometimes quite slow. Some DBTs also tried to “game the system by over-designing their product in order to have some room for design tradeoffs later. Fortunately, concurrent engineering and open access to data made the over-design strategy transparent to everyone involved. Consistent and open analysis using M&S technology meant every DBT’s cards were on

the table. Therefore, honest coordination and sound engineering judgment could eventually prevail.

In order to ensure a smoothly flowing design process, senior Boeing management asked the DBTs to get inputs from the customers into the design process and then enter these inputs as critical design elements. This action got the DBTs into direct contact with airline personnel. DBTs were sent to talk directly with airline mechanics and service personnel in order to get their point of view on the designs. One specific goal was to find out directly from the gate mechanics what information they needed to efficiently service the airplane.

Two examples of the knowledge gained from the field illustrate the value of human experience and some limitations of M&S alone. In one of the electronics bays there is light centered directly in the ceiling. One of the mechanics pointed out that whenever he was the bay and leaned over to work, he inevitably blocked the light and had to use a flashlight. The simple solution was to install lights at the corners of the enclosure. However, as the result of this seemingly insignificant observation, Boeing realized that M&S could not adequately predict human factors issues and design criteria. Lighting and illumination could be added to the aircraft model, but only after human factors studies discovered the illumination issue.

Another example came when the team opened a lower hold to check on a part and discovered hundreds of small salt packets that had fallen off food trays and found their way down below the passenger compartment. The combination of salt and moisture condensing on the inner skin of the aircraft produced a corrosive salt-water bath splashing about on the inside of the aircraft. This may seem like a trivial matter, but it is

one of the issues Boeing is struggling with. How to get M&S to anticipate the problems that can and do happen in the real world? M&S cannot provide field service data or practical servicing tips. Human experience with the system is the only way to discover these problems.

The DBTs had to gather and study this information using the old design methodologies and then synthesize what they learned into knowledge the designers could actually use. In the past, middle managers, sometimes derisively known as “gray-beards”, would monitor the design process and check for problems. Although with M&S technology, the aircraft designers were much more capable of finding problems and coordinating requirements without as much management oversight. However, M&S did not prevent the designers from making errors of omission. Design requirements make more sense to the individual workers when the information was part of a model instead of an abstract and seemingly arbitrary requirements list. Nevertheless, the combination of DBTs along with M&S technologies did lead to a mature and stable design much earlier than the B-757 program before it. Consequently, the B-777 test and certification processes also went much more smoothly. Flight-testing went according to schedule with no major delays for either redesign or engineering analysis.

Engineering Results

One of Boeing’s key goals for the B-777 was "Day One Service Readiness", by conducting extensive testing and integration throughout the program. Boeing used M&S technology as an integral part of the ground-testing program to help work out the flaws before production. The 500,000 square foot, \$110 million Integrated Aircraft Systems Laboratory (IASL) is the newest addition to Boeing’s test facilities. It contains over \$250

million of test equipment. According to Boeing engineer Chris Adams, the IASL is an example of the philosophy shift from "repairing" toward "planning" in the B-777 effort.

Aircraft systems that in the past had not been tested together until the first flight were integrated and tested in the IASL. "Aircraft Zero" or the "B-777 without the skin", as the integrated systems were called, had been "flown" or simulated for many hours before the first aircraft flight over Seattle. This testing was useful in moving developmental work forward and allowed early ETOPS certification by performing statistical analysis of mean time between failures for the digital avionics suite.

The FAA required a full-scale failure test of the wings on the second production airplane and the results were quite impressive. The test results validated the CATIA component level analysis almost exactly. Over 2,000 individual strain gauges were used to instrument the plane with 500 miles of cables relaying the data to the CATIA system to validate the structural analysis model. Each wing was subjected to 500,000 pounds of force and the wing tips deflected 24 feet before failing at 154 percent of maximum flight loads. This applied force represented a factor of safety of 1.5 times the loads experienced during a 2.5-g recovery from a dive. During the test, the right wing failed 0.020 seconds before the left wing. This is just above the 152 percent target design criteria and almost exactly as predicted by the CATIA engineering model of the completed wing assembly.

The B-777 also had the most extensive flight-test program of any previous Boeing airplane. Nine airplanes were used with engines from three manufacturers. Before the test program was completed, all nine airplanes flew nearly 7,000 hours for more than 2,900 total flights. The flight-testing program lasted about two years with customer involvement of flight and ground crews in the latter stages of the test program. All of the

B-777s involved in testing carried large amounts of instrumentation and data recording equipment. The data collected in-flight was used to validate the aircraft model—as a complex system—developed during the design and production process.

Handling qualities testing during the first two months of the flight-test program proved the value of the simulation and analysis of the digital flight control system. Very few changes were made in the flight control system software as the result of in-flight handling qualities evaluations. However, the M&S effort was not perfect and small adjustments to pitch control gains, turn coordination scheduling, and the flaperon commands were made as the result of flight-test.

M&S also did not predict pilot induced oscillation (PIO) problems that were uncovered early in the flight-test program. The most significant event occurred when a new test pilot was checking out in the B-777. During the de-rotation after landing, a pitch PIO developed which went for at least three cycles and became a flight hazard before intervention by the other pilot. This PIO was the result of a rapid application of elevator followed by an equally rapid check that led to the elevator actuator becoming saturated by control inputs. Some unexpected oscillations were also encountered during autopilot mode transitions and mistrim takeoff conditions with large and abrupt elevator commands. However, the oscillation tendencies were easily controllable by the pilot.

Another oscillatory mode was discovered during flight-test that was not predicted by the M&S of the aircraft before flight-testing. This oscillation was classified as Airplane-Pilot-Coupling (APC). This was a three-Hertz (Hz) body-bending mode triggered by rapid pitch commands. This mode was most often encountered as pilots increased the frequency of their control inputs as the aircraft entered the landing flare. This oscillatory

mode was not a hazard to flight safety, and was quickly fixed with software changes, which dampened the three Hz feedback to the control system. In the end, the flight-test team did recommend that some additional work be done in modeling man-in-the-loop oscillatory motions. The flight-test team also recommended that the limitations of modeling complex systems be incorporated into the design requirements for the next generation of Boeing aircraft.

Fortunately, the Boeing test team had extensive experience with M&S, aircraft flight control models, and variable stability aircraft. Because M&S was an integral part of the engineering and design effort of the B-777 program from the very start, the flight-test team better understood both the capabilities and limitations of M&S. The flight-test team was then able to make sound recommendations to the design engineers. Both the pilots and the project engineers realized that M&S could not anticipate all the engineering deficiencies of a complex system such as a modern jet aircraft. The combination of flight-testing and modeling is required—especially as systems become more complex. Modeling provides prediction and analysis; flight-testing provides real-world engineering data and model validation.

Evaluation M&S for Flight-Testing Complex Systems

The aerospace industry is increasingly becoming an information processing industry. Computers have moved well beyond basic control functions. Instead, they can create a “virtual” prototype, which is then assembled and tested in cyberspace. Managing data to make design, production, and testing less expensive is a prerequisite to sound engineering and design practices. The “airplane in a computer” concept pioneered by the B-777 program has become the baseline for future aircraft design programs at Boeing.

However, the costs of building an “an airplane in a computer” are still quite substantial. A CATIA workstation with the appropriate software costs approximately \$10,000.⁶² Therefore, 2,200 workstations cost the company a little more than \$22 million. Although, the specific costs of the mainframe computing cluster and data storage facilities were not available for this research, they added significantly to the overall costs of the program.

The costs of M&S hardware and software dedicated to the B-777 program were well above the \$22.5 million dollars required to build a non-flying prototype. If skipping the prototype phase was the only benefit of investing in M&S technology, then M&S would not be cost effective. However, the non-flying prototype is a sunk cost. There are no follow-on benefits and the prototype eventually must be scrapped. On the other hand, M&S hardware and software has a useful life of three to five years before becoming obsolete and can be used for other programs. The IASL was a \$110 million investment in M&S, but it will serve the needs of all Boeing’s aircraft programs for many years to come. M&S also permits aircraft design data to be archived easily and inexpensively so that costly lessons learned one design and test program can be used on the next generation of aircraft.

Therefore, the costs of M&S for a complex system cannot be easily justified for a single program. The commitment to model a complex system brings about significant changes to the way an entire organization does business. Boeing is in the business of designing and building airplanes and needs to cut costs while simultaneously staying ahead of the competition technologically. M&S can only be cost effective for a complex

Note

⁶² These figures are the best available estimates as of 1 May 1998 from the Boeing

system such as the B-777, when the company is willing to commit to M&S for the long term. The company must also be willing to accept the organizational changes required to integrate M&S into the entire design, production, and testing process.

In order to ensure quality during the design and testing process, M&S must provide valid engineering data. In the case of the B-777, the engineering validity of the models was excellent. All testing of the aircraft at the component level showed outstanding form, fit, and function. The accuracy achieved with M&S was simply unattainable with standard engineering and design methods. In fact, the first production B-777 was also the first aircraft ever assembled by Boeing that did not require shimming when the fuselage was constructed. Likewise, the wings alignment was within the accuracy of the instrumentation. All ground and flight-test data at the component level matched M&S predictions. Therefore, the engineering validity of the M&S data was excellent—even for a complex system such as the B-777.

Nevertheless, Boeing did push the technological boundaries with the B-777 program. There were some problems at the systems level with the comprehensiveness of the M&S effort. For example, the PIO problem encountered during flight-test was not predicted by any systems level model of the aircraft. In addition, the APC difficulties encountered during landing were completely unforeseen by M&S. Fortunately, Boeing's flight-test team had extensive experience with both digital flight controls and the hazards associated with flight-testing these systems. These problems were easily fixed, but only because sound engineering judgments were made by experienced people. M&S augmented but did not replace the human element of designing and testing aircraft.

Notes

Commercial Aircraft Corp., courtesy of the Boeing 767 division.

The aerospace industry's dependency on M&S technology is mushrooming. Complex systems models are not yet comprehensive tools for designing and testing airplanes. The problem of building and maintaining comprehensive models is being made even more difficult by rapidly changing information technologies. Boeing estimates that only one-third the number of software applications in use today will be here in another fifteen years.⁶³ Cristoph W. Klomp, who leads Boeing's 737 software office, says: "This company would collapse if there were no IT (information technology) services, but exploration of these services is still very, very shallow."⁶⁴ Boeing has found that despite the remarkable improvements in M&S technology, M&S still has significant limitations when modeling complex systems. Computer problems still vex projects temporarily and delay programs, and even "expert" systems cannot provide sound engineering judgment.

Frank McCormick, the lead engineer for the B-777 autopilot system, said:⁶⁵

There are utilities and tools that have been around for a long time that help with certain aspects of the job...with the bookkeeping aspects...What everyone wants and no one has found is a magic utility that will help you develop a safe, complete, unambiguous, and non-conflicting requirements.

That is still requires human experience and sound engineering judgment. Computers only aid the designers and store the data. Flight-test will still be required and the engineering decision process is still very much a human activity.

Note

⁶³ Michael Mecham, "Boeing Translates 737 to Digital Age," *Aviation Week and Space Technology* Vol. 147 no. 14 (Oct. 6, 1997): (48–49).

⁶⁴ *ibid.*

⁶⁵ Mecham, "Aerospace Chases the Software Boom" 48.

Chapter 5

The Future of Modeling and Simulation for Flight Test

The day is rapidly approaching when a significant portion of aircraft design and engineering, especially the test and evaluation phase, will be replicated in an artificial environment. Advances in computer technology are making this possible, and declining resources are making it mandatory. M&S is still expensive, but not prohibitively so. Moreover, the real costs of M&S are declining while capabilities are rapidly increasing.

Currently the capabilities of M&S are doubling approximately every eighteen months. This is the case for three reasons. First, the processing speeds of computers are doubling about every twenty-four months and are expected to continue to do so in the future. Second, the modeling techniques and computational methods are becoming more sophisticated. We can now model complex physical phenomenon such as turbulent flowfields that were not well understood only a few years ago. Third, the modeling efforts used in one program usually are easily importable into another M&S project.

The three factors of increased computational power, more sophisticated computational methods, and cross-platform applicability of computational techniques are causing these extraordinarily rapid advances in M&S technologies. The speed of technological advance is changing the way systems are developed and fielded. M&S is now a critical aspect of most major weapons systems development. The flight-test

community must be proactive in utilizing this new tool. The ability to conduct effective M&S must be developed as an integral part of future flight-test programs.

Evaluation of Cost, Engineering Validity, and Comprehensiveness

All three programs discussed in this paper have made significant progress towards meeting the challenges set out by senior Air Force leadership in *A New Vector for Air Force Modeling and Simulation*. Although M&S is not free, it is almost always more cost-effective than testing alone when applied at the physical component or the closed-loop system level. It can be significantly more cost-effective than traditional engineering techniques when applied to a complex system such as the B-777, if the organization is willing to commit to technological and organizational changes.

The engineering validity of M&S was excellent in all three cases studied during this research. The accuracy of the models was equal to or better than traditional engineering methods. The variance between flight-test data points and the M&S predictions were barely measurable by the flight-test instrumentation. For example, the B-1B flare trajectory predictions were within one foot of the flight-test data points. This was the most accurate result possible, because the intense brightness of the burning flare saturated the film in a one foot circle around the flare. Therefore, the instrumentation accuracy was plus or minus one foot, which was the same accuracy as the trajectory model.

In the case of the VISTA, there were very few measurable differences between the M&S data points and the flight-tested data on the F-22. However, the VISTA did not have as large a flight envelope as the F-22 and the sampled data from the VISTA had slightly different statistical characteristics than the F-22 data taken over the complete flight envelope. Likewise with the B-777, the individually modeled data points were

extraordinarily accurate. Component parts were so accurately engineered that no aircraft prototype was required to check, form, fit, and function before production. Therefore M&S was more accurate than traditional engineering methods for the B-777 program at the physical component level, but the computer model had a limited range of accurate predictions. The limitations of M&S become more significant as the model increased in scope and complexity.

A modeling effort often increases in scope and complexity by building upon previous M&S work. Engineering teams often take the computational methods and data used on a previous project and update them for the task at hand. This was certainly the case in the B-1B flare strike project. The team began by taking B-1B models from earlier programs and modifying them to suit project requirements. Aeronautical data from earlier projects were applied to the flare trajectory model and spin-off technologies from the F-22 program were also used. Despite the myriad of sources used to construct the B-1B flare trajectory model, it completely and accurately predicted the engineering outcomes of flight-test. Because the scope of the B-1B modeling effort was limited to the physical component level, the model was provided comprehensive solutions to the problem at hand.

In the case of the VISTA, the M&S effort provided comprehensive solutions within the limited flight envelope of the VISTA simulator. There were no unexpected results from the VISTA flight tests. The F-22 response matched the VISTA's almost exactly within a limited but known range. Nevertheless, it was possible to draw invalid engineering solutions from the VISTA by trying to extrapolate results by statistical analysis beyond the valid range of the model. The actual F-22 parameter data had slightly

different statistical distributions than the VISTA data because the VISTA was only capable of sampling flight parameters in a more restrictive flight envelope.

However, the B-777 system was so complex that the model was not comprehensive enough to predict all the significant engineering results from flight-test. Minor changes to flight control software were required after flight-testing and some unexpected modes of motion were discovered in test that were not predicted from M&S. These unexpected modes of motion did not cause a hazard during flight-test, because the test crews were aware of the limitations of M&S for a sophisticated project such as the B-777. The crew knew the theory of digital control systems and understood the potential hazards. However, the unexpected results might have been a severe hazard for a less experienced crew. The risk of modeling without flight-testing is too great to rely completely on M&S for complex systems. Figure 15 below summarizes the evaluation of costs, engineering validity, and comprehensiveness for each of the cases in this research.

	B-1B Physical Model	Flare Comp.	VISTA Closed-Loop Model	Boeing Complex Model	777 System
Costs	\$950,000 CFD	with modeling	VISTA modeling at \$8,000/hr.	Approx. million M&S	\$250 long-term investment
	\$3.5 million modeling	without modeling	F-22 flight-test at \$20,000/hr.	\$22.5 million/prototype without modeling	
Engineering Validity	Within instrumentation accuracy	flight-test accuracy	Within instrumentation accuracy	flight-test accuracy	Errors smaller than standard engineering methods
Comprehensive	Completely comprehensive		Completely comprehensive within a limited but <i>known</i> range		Not comprehensive because some flight- test results not predicted by M&S

Figure 15: Evaluation of Case Results

Lessons Learned for Future Flight-Testing

Four very important lessons can be learned for the future of flight-test from these three case studies. First, changes in tactical doctrines for a weapon system can generate new flight test requirements for that system. This lesson is particularly important as weapon systems see longer life spans and their mission requirements sometimes change radically. Both the flight test community and the operational users must maintain a constant dialog with each other to ensure that such doctrine changes and corresponding test candidates are identified as early as possible.

Second, the concept and application of integrated test and evaluation provides rich dividends. When the flight testers, ground testers, modelers, simulators, program managers, and vendors proactively pool their resources throughout the design, production, and test phases, the benefits in cost and schedule reductions, as well as performance increases, are superb.⁶⁶

Third, the recent leaps in technology within the M&S community, and the subsequent maturation of the capabilities, have provided a powerful and vital tool for use in many future flight test programs. The flight test community should make a point to seek out these capabilities continually in the design of every flight test program. M&S will never replace the need for flight test, especially since models can never be fully validated without flight test data, but M&S can certainly assist in smarter, more informed test planning and conduct.⁶⁷

Note

⁶⁶ Dr. David C. Brown, "A Tester Prepares for Synthetic Acquisition," *International Test and Evaluation Association Journal*, June/July 1996,14-17.

⁶⁷ Dr. Patricia Sanders, "Modeling and Simulation: Challenges for the Test and Evaluation Community" presentation to an International Test and Evaluation Association Workshop, Las Cruces, New Mexico, 13 December 1995.

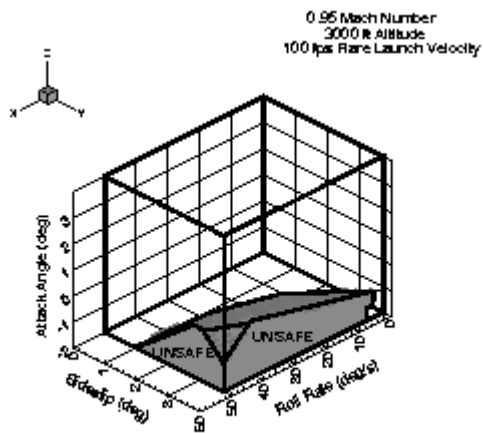
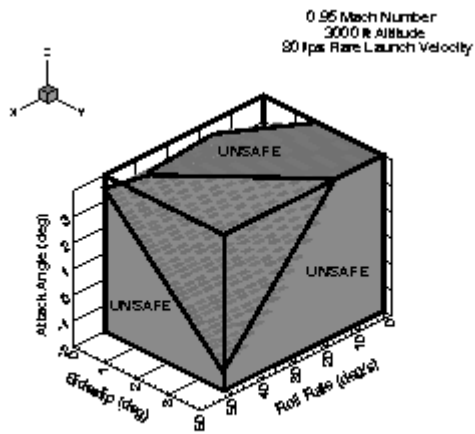
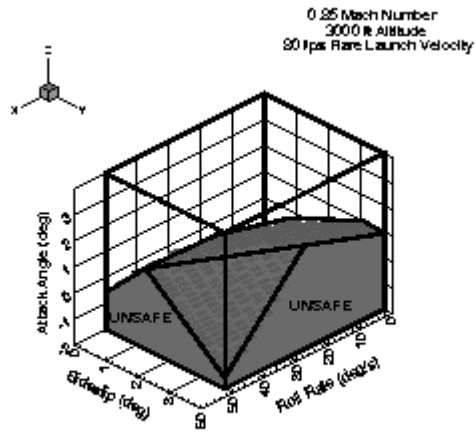
Finally, the design of flight test instrumentation should include elements required for model validation, even if those elements are not immediately required for the flight test itself. The Undersecretary of Defense, Dr. Paul G. Kiminski has endorsed this measure, in a speech to the International Test and Evaluation Association.⁶⁸ This lesson could easily be extrapolated to actually include objectives in the flight test plan to provide model validation data. With a constant feedback loop established, the test and evaluation community would directly invest in itself with *A New Vector* for its future.

Note

⁶⁸ Honorable Paul G. Kiminski, Undersecretary of Defense for Acquisition and Technology, Address to the International Test and Evaluation Symposium, Huntsville, AL, 3 October 1995.

Appendix A

Modeled Safe Deployment Envelope of MJU-23B Flares



Models of Flare Ejection Velocity on Flare Deployment Envelope

Appendix B

VISTA Technical Specifications

Handling Qualities Simulation Capabilities

Short Period Natural Freq.	0 to 15 rad/sec
Short Period Damping	-0.1 to 1.1
Nz/alpha	1 to 100g/rad
Stick Force/g	1 to 200lbs/g
Phugoid Natural Freq.	0 to .5 rad/sec
Phugoid Damping	-0.3 to 1.0
Dutch Roll Natural Freq.	2 to 8 rad/sec
Dutch Roll Damping	-0.1 to 1.0
Roll/Spiral Mode Natural Freq.	0 to 5 rad/sec
Roll/Spiral Mode Damping	-0.1 to 1.0
Roll/Sideslip	0 to 10
Variable Time Delay	0.01 to 0.5 sec
Lead/Lag	1 to 63 rad/sec

Aircraft Operating Envelope

Sideslip	+/-10 degrees	
Side Acceleration	+/-0.5g	
Landing Speed	130-160 Kts	
Direct Lift	+/-1g in 0.2 sec	
Pitch Pointing	+/-7	deg
Max. Normal Acceleration (g's)	Delta Alpha -2.4/+7.33	

Appendix C

Boeing 777 Technical Specifications:

Length	209' 1" (64 meters)
Wing span	199' 11" (61 meters)
Height	Unknown
Max Take Off Weight	535,000 lb. (242,672 kg)
Speed	Mach 0.84
Range	4,353-5,332 miles (3,780-4,630 nautical miles)
Armament	None
Crew	Two Pilots plus cabin crew
Unit cost	\$128.0 to 170.0 million
Inventory	N/A
Constructor	Boeing

Glossary

ACC	Air Combat Command
AEDC	Arnold Engineering Development Center
AFFTC	Air Force Flight Test Center
AFMC	Air Force Material Command
AGL	Above Ground Level
ALC	Air Logistics Center
ATIMS	Airborne Turret Infrared Measurement System
ATIS	Airborne Test Instrumentation System
CAD	Computer Aided Design
CATIA	Computer-Aided, Three-Dimensional Interactive Application
CFD	Computational Fluid Dynamics
CTF	Combined Test Force
DBT	Design Build Team
DOF	Degrees of Freedom
DSO	Defensive Systems Operator
DTUC	Data Transfer Unit Cartridge
ETOPS	Extended Range Twin-Engine Operations
fps	feet per second
GPS	Global Positioning System
HUD	Heads Up Display
IAS	Indicated Airspeed
IASL	Integrated Aircraft Systems Laboratory
KBE	Knowledge Based Engineering
LRU	Line Replaceable Unit
M	Mach Number
MDA	Milestone Decision Authority
MSL	Mean Sea Level

NAWCWPNS NFOV	Naval Air Warfare Center, Weapons Division Narrow Field of View
OSO	Offensive Systems Operator
PIO	Pilot Induced Oscillation
SPO SSO	Systems Program Office Systems Sustainment Office
TAS	True Airspeed
VISTA VSS	Variable Stability In-flight Simulator Test Aircraft Variable Stability System
WFOV	Wide Field of View

Algorithm. A step-by-step problem-solving procedure, especially an established, recursive computational procedure for solving a problem in a finite number of steps.

Alpha. The variable commonly assigned in aerodynamic equations to angle of attack.

Angle of attack. The angle between the relative wind and the chord line of an airfoil.

Beta. The variable commonly assigned in aerodynamic equations to sideslip.

Benchmark. The activity of comparing the results of a model or simulation with an accepted representation of the process being modeled.

Benchmarking. The comparison between a model's output and the outputs of other models or simulations, all of which represent the same input and environmental conditions.

Black Box Model. A model whose inputs, outputs, and functional performance are known, but whose internal implementation is unknown or irrelevant. For example, a model of a computerized change-return mechanism in a vending machine, in the form of a table that indicates the amount of change to be returned for each amount deposited.

Boundary Condition. The values assumed by the variables in a system, model, or simulation when one or more of them is at a limiting value at the edge of the domain of interest.

Built-in-Simulation. A special-purpose simulation provided as a component of a simulation language; for example, a simulation of a bank that can be made specific by stating the number of tellers, number of customers, and other parameters

Built-in-Simulator. A simulator that is built-in to the system being modeled; for example, an operator training simulator built into the control panel of a power plant such that the system can operate in simulator mode or in normal operating mode.

Chimera overset mesh methodology. Computational techniques using simplified models of parts of a complex shape connected by a grid or coordinate system.

Degree-of-freedom. The ability of a free body in space to move by either translation or rotation along an axis. *Note: six degrees of freedom implies the body is free to rotate and or translate unconstrained.*

Empennage. The tail section of an airplane to include both the horizontal and vertical stabilizers.

Empirical. Relying on or derived from observation or experiment.

Euler equations. First order differential equation relating the change in momentum of a gas to the force.

Gaussian Distribution. A theoretical frequency distribution for a set of variable data, usually represented by a bell shaped curve symmetrical about the mean.

Inviscid. The property of a fluid having negligible or no resistance to flow

Monte Carlo methods

Navier-Stokes equations. A series of differential equations relating the change in momentum of a gas to the forces applied accounting for resistance to flow (viscosity) and compressibility of the gas.

Sideslip. The angle between the longitudinal axis of an aircraft in flight and the direction of the airflow.

Spectrometer. An instrument used to determine the intensity of various wavelengths in a spectrum of light.

Stochastic. Involving or containing a random variable or variables.

Taylor series expansion. An approximation of the solution to a mathematical function which uses an infinite series of derivatives of that function.

Transonic. Of or relating to aerodynamic flow or flight conditions at speeds close to the speed of sound.

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