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NORTH ATLANTIC TREATY ORGANIZATION

RESEARCH AND TECHNOLOGY ORGANIZATION

BP 25, 7 RUE ANCELLE, F-92201 NEUILLY-SUR-SEINE CEDEX, FRANCE

RTO AGARDograph 300

Flight Test Techniques Series – Volume 19

Simulation in Support of Flight Testing

(la Simulation pour le soutien des essais en vol)

This AGARDograph has been sponsored by the SCI-055 Task Group, the Flight Test Technology Team of the Systems Concepts and Integration Panel (SCI) of RTO.

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Edited by
Dennis O. Hines

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Simulation in Support of Flight Testing

(RTO AG-300 Volume 19)

Executive Summary

Flight testing continues to remain an essential step in the development or modification of an aircraft. Modern fixed wing aircraft are highly complex systems that push the edges of aerodynamic, propulsion, and control system technologies. Many of these technologies are integrated together and dependent upon each other. Certainly, modern military aircraft ranging from the F-22 to the EF2000 push the boundaries of capabilities that can be built into an aircraft. Commercial transportation such as Airbus's A310 and Boeing's 777 incorporate many aircraft advances that were first used in military airplanes. The ever-increasing complexity of the aircraft presents new challenges to those who are involved in the flight testing of those vehicles. For over 40 years simulation has played a key role in flight testing. As the aircraft continue to evolve in complexity, the role of simulation continues to grow. Every major aircraft developer, whether they are commercial or military, depends on the use of simulation to some degree. The application of these simulations to flight testing is an important aspect of the aircraft's development. Each year, dozens of symposium and conferences are held around the world to discuss simulation and its uses. As computer technology continues to evolve at an accelerating pace, the field of simulation continues to expand with it. Unfortunately, very little has been written to document how simulation can be effectively used to support flight testing.

The purpose of this AGARDograph is to provide an introduction to simulation and how it can be used to support flight testing of fixed-wing aircraft. Simulation of rotary wing aircraft is a similar but different subject and should be covered in a separate report. This AGARDograph has been written from the perspective of trying to provide a flight test engineer the basic information in how to effectively use simulation to support flight testing and what must be considered when developing a simulation that is to be used for flight test support. The first chapter introduces the reader to simulation and its role in supporting flight testing. Chapter two provides a history and overview of simulation and the benefits of using it to support testing. Chapter three provides an in-depth discussion of the various types of simulation and the unique test role played by each of those simulations. Chapter four focuses on what needs to be considered when developing a simulation including the types of models, the visual scene presented to the pilot, and how to verify and validate the simulation. Chapter five presents a discussion on how to apply simulation to a flight test program. Chapter six presents some ideas as to where simulation in support of flight testing is headed in the future. The book ends by drawing some conclusions. First, the type of simulation is based on the intended use of the simulation. Second, the simulation models must be built from adequate data and they must be verified and validated for use in the simulation. Third, a simulation visual system is required and must be tailored to fit the designed use of the simulation. Fourth, simulation will continue to be a tool used to increase the effectiveness and efficiency of flight testing and should not be used as a total substitute for flight dynamics flight testing.

la Simulation pour le soutien des essais en vol

(RTO AG-300 Volume 19)

Synthèse

Les essais en vol continuent de représenter une étape indispensable dans le développement ou la modification d'un aéronef. Les aéronefs à voilure fixe modernes sont des systèmes très complexes à la pointe des technologies de l'aérodynamique, de la propulsion et des systèmes de pilotage. Beaucoup de ces technologies sont intégrées et interdépendantes. Il est certain que les spécifications des avions de combat modernes, allant du F22 à l'EF 2000, se situent aux limites des capacités pouvant être intégrées dans un aéronef. Les avions commerciaux tels que l'Airbus A310 et le Boeing 777 incorporent bon nombre d'avancées technologiques utilisées d'abord dans des avions militaires. La complexité sans cesse croissante des aéronefs présente de nouveaux défis à relever pour ceux qui sont impliqués dans les essais en vol de ces véhicules. Depuis plus de 40 ans, la simulation joue un rôle clé dans les essais en vol. Avec l'évolution de la complexité des aéronefs modernes, le rôle de la simulation ne cesse de s'amplifier. Chaque avionneur, qu'il soit commercial ou militaire, fait appel, dans une certaine mesure, à la simulation. L'application de ces simulations aux essais en vol est un aspect important du développement d'un aéronef. Chaque année, des dizaines de conférences sont organisées dans le monde entier pour discuter de la simulation et de ses applications. L'évolution des techniques de simulation suit l'évolution fulgurante de l'informatique. Malheureusement, il n'existe que très peu d'indications sur l'application de la simulation aux essais en vol.

Cette AGARDographe a pour objet de fournir une introduction à la simulation et à sa mise en oeuvre pour le soutien des essais en vol des aéronefs à voilure fixe. La simulation du vol des aéronefs à voilure tournante est un sujet distinct, qui mériterait d'être traité dans un autre rapport. Cette AGARDographe est destiné aux ingénieurs d'essais en vol. Elle fournit un certain nombre d'informations essentielles concernant la mise en oeuvre efficace de la simulation pour le soutien des essais en vol, ainsi que les différents éléments à prendre en compte lors du développement d'une simulation pour le soutien des essais en vol. Le premier chapitre présente la simulation et son rôle dans le soutien des essais en vol. Le chapitre deux fournit un historique et un aperçu de la simulation et des avantages liés à sa mise en oeuvre pour le soutien des essais en vol. Le chapitre trois présente une discussion détaillée des différents types de simulation et du rôle unique que joue chacune de ces simulations dans les essais en vol. Le chapitre quatre porte sur les éléments à prendre en considération lors du développement d'une simulation, y compris les différents types de modèles, la scène visuelle présentée au pilote, et la vérification et validation de la simulation. Le chapitre cinq traite de l'application de la simulation aux programmes d'essais en vol. Le chapitre six présente un certain nombre d'idées concernant l'avenir de la simulation en tant qu'outil pour les essais en vol. L'ouvrage se termine par un certain nombre de conclusions. En premier lieu, le type de simulation à employer dépend de son utilisation finale. En deuxième lieu, le modèle de simulation doit être conçu à partir de données adéquates, vérifiées et validées pour utilisation. En troisième lieu, il y a lieu de prévoir un système visuel de simulation conçu en fonction de l'application de la simulation. Et enfin, la simulation restera un outil permettant d'améliorer la qualité et l'efficacité des essais en vol. Elle ne doit pas être utilisée pour remplacer en totalité les essais en vol de la dynamique du vol.

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Preface

For over 40 years simulation has been an important tool supporting flight testing. The use of simulation has improved flight test planning, execution and safety. The incredible growth in computational capabilities has created new possibilities on how modeling and simulation can be used to support flight dynamics flight testing. However, even with improved computers, high-fidelity simulations still depend on the ability of the engineering team to create models that accurately represent the aircraft or the environment that they are testing. Flight dynamics flight testing inherently involves non-linear aerodynamics that can be very difficult to accurately model. Because of these factors, the use of simulation will never replace flight testing as a method to clear the aircraft's flight envelope. Instead, simulation is a tool that greatly improves the efficiency and effectiveness of a flight test program, but it must be used in conjunction with the actual testing.

The various types of simulation can support all aspects of a test program. It is critical that the correct type of simulation be matched to the appropriate test requirement. To make simulation an effective tool there are many factors that must be considered when building a flight test simulation. The level of fidelity of the models, simulator cockpit, and simulator out-the-window visual scene must be well understood by the whole test. Inherent in this is a rigorous verification and validation process that must be followed by the engineering team. All team members must understand the limitations of the flight test simulation when using it. The simulation tool must be properly applied to obtain maximum effectiveness.

This AGARD report provides an in-depth look at how simulation is used to support flight dynamics flight testing. The aim was to provide guidance to flight test engineers who are interested in using simulation as a tool on their test program. The information contained herein provides the test engineer with the information to justify, build, validate and use a flight simulator as an integral part of a flight test program.

1. INTRODUCTION

Simulation plays a key role in the successful conduct of a flight test program. Over the last 40 years, simulation has played a vital role in increasing the safety and efficiency of flight testing. Modeling and simulation (M&S) is a tool to support testing and will never supplant the need to conduct actual flight testing on a real airplane, in a real environment. Results obtained from running simulations need to be analyzed in context with actual test results to properly characterize an aircraft's limitations. The information presented in this document proceeds from this basis.

The use of simulation in the life-cycle of an aircraft is both extensive and varied. Simulations are used from the beginning of a program to help determine requirements all the way through developing the logistics involved in operating and maintaining the aircraft. Many of the technical disciplines involved with the aircraft development make use of simulation. In flight testing, simulation is used to support structures and flutter tests, stores separation tests, flight dynamics tests, avionics and electronic combat tests, as well as total weapon system's effectiveness tests. While all of these test disciplines use simulations, the types of simulation and the complexity of the simulation may vary greatly. For example, structures simulations require highly-detailed finite element type models of the aircraft's skin and structural components, but they do not require detailed aerodynamic models. Conversely, flight dynamic simulations, need very detailed aerodynamic models, but only simplified structural models, if any at all.

This report is concerned with the use of simulation to support flight dynamics testing of fixed-wing aircraft. Flight dynamics testing is defined to include stability and control tests, handling qualities testing, digital flight control testing, and associated type tests. For this report, it does not include performance or propulsion testing, although flight dynamics testing is dependent on performance and propulsion tests to Verify and Validate (V&V) models such as drag and engine models that are used in a flight dynamics simulation.

This report is structured to step the reader through a complete discussion of developing and using simulation to support flight dynamic's flight testing. Section 2.0 provides a brief overview of the history of simulation to help put the rest of the report into perspective. This section also deals with the rationale for building and using a simulation. Often, this is most difficult task facing a flight test engineer. While the prime airframe contractor may build many simulations as part of the design and development process, often there is a certain amount of reluctance on the part of the aircraft program manager to spend additional money on developing simulations that are used in support of flight testing. This section provides a discussion of the general benefits of using simulation to support flight testing that may be useful in persuading future program managers to spend the money on simulation development.

Section 3.0 provides a detailed discussion on the types of simulations that are used to support flight dynamics testing. There are five major categories of simulation: analytic (non real-time); engineering/Man-in-the-Loop (real-time); Hardware-in-the-Loop (HWIL); Iron Bird; and In-flight simulation. In each of these categories a detailed discussion is presented on the intended use of the simulation and the resources required to construct, operate and maintain each type of simulation. Examples of each type of simulation are provided to help understand the details.

Section 4.0 provides an in-depth discussion concerning the development of each type of simulation. The first topic covered is a discussion on the requirements, or intended use of each type of simulation. Before building any simulation, the simulation engineer must have a good grasp as to how the flight test engineer intends to use the simulation. This intended use will drive the complexity of the models required, hardware and software, as well as the amount of V&V required for the simulation. Section 4.2 delves into the various modeling aspects associated with flight dynamics simulation. This section is intended to give the flight test engineer an appreciation for the tradeoffs in model development that must be made in developing any simulation. In order to understand the results, the test engineer must have a firm understanding of the underlying assumptions from which the models were constructed. Model development, as well as V&V of the simulation (section 4.6) requires a close partnership between the simulation engineer and the test engineer. Each one relies upon the other to provide the necessary information as well as an understanding of the simulation use and tradeoffs. Section 4.3 discuses the various aspects associated with cockpit development. Both this topic and section 4.4, which covers visual scenes, are applicable primarily to real-time, HWIL, and iron bird simulations. The interface with the pilot and his perception of the simulated outside world is critical for acceptance and ultimate validity of the simulation as compared to reality. There are many cost/performance tradeoffs that must be made in relation to cockpit and visual scene development. Too little authenticity will result in a simulation which does not seem realistic to the pilot and therefore of limited utility. Conversely, there can be too much money invested to provide as realistic as possible simulation, which may not be necessary for the types of testing the simulation will support. The cockpit and visual scene development are often secondary considerations to the test engineer compared to the modeling, however, these elements can not be neglected and must be budgeted for and designed into the simulation early on during the requirements definition phase.

There are eight main purposes of flight test simulation. These are: 1. Test planning/flight envelope clearance determination; 2. test maneuver definition; 3. anomaly investigation; 4. test scenario development; 5. verification and validation of software targeted for flight control systems; 6. aircraft failure mode effects testing; 7. flight test training; 8. Limit cycle oscillation Each of these uses present different and challenging problems to the flight test engineer as well as the simulation engineer. These challenges will be explored in detail in this report. This report also provides a recommended correlation between the purposes and the simulation types that are best used to meet the demands of that purpose. Additionally, some examples in each category are provided as real-world examples currently in use.

Section 5.0 details how a test engineer would design a flight test program using simulation as a tool. This section correlates closely with the V&V discussion since one of the main purposes of actual testing is to gather data to validate the models.

Section 6.0 provides a glimpse into the future of simulation and how it relates to flight testing. Simulation technology is rapidly evolving and new capabilities are constantly being developed. This evolution will continue to drive how testing uses M&S as a tool.

Finally, section 7 provides a summary of the report and some conclusions. It is safe to state right now, that simulation in support of flight testing is here to stay, and there is a growing demand to further increase its use. The question becomes how much testing can really be replaced by simulation before sacrificing safety and increasing the cost of simulation prohibitively to make it worthwhile. The test community must come to grips with this dilemma. Simulation is not a panacea for all test problems, but a valuable tool that must be used cautiously and wisely in the course of a test program.

2. THE ROLE OF SIMULATION

The role of simulation in support of flight testing has been evolving almost since the beginning of manned flight. Aircraft designers and testers have come to realize the benefit of simulation in order to produce an aircraft that can be safely tested and operated. These simulations focus primarily on envelope expansion and gaining confidence that the aircraft is safe to begin flight testing. From that perspective, the use of simulation is expected as part of the aircraft development.

2.1. Definitions of Modeling and Simulation

In order to discuss the use of M&S, it is necessary to provide a definition of terms. A model is a physical, mathematical, or otherwise logical representation of a system, entity, phenomenon, or process. A simulation is a method for implementing a model over time. Models can be written in a variety of computer languages, but for T&E simulations, FORTRAN and C++ are the most common language used. A simulation can contain one or many models whose execution is controlled by an executive. This simulation executive controls the sequence of execution of the models, the time step or frequency of execution, the data transfer between models, and the output of the data to be used in analysis. A more detailed description of a simulation is provided in Section 4.2.

Real-time is defined as a system that is capable of reacting to external events as they happen. (Reference 1). A real-time system has absolute time requirements that it must meet. For example, a HWIL simulator that interfaces with a digital model must be synchronized so that the aircraft's avionics' messages are accurately passed to the software models and back again at the correct rate and with proper timing. Real-time systems must be able to handle multiple and unrelated inputs but they still must be deterministic. For flight dynamics, real-time usually refers to Man-in-the-Loop, or HWIL simulations.

Non real-time is defined as simulated time that does not operate at the same rate as actual time. These simulations can either run faster or slower than real-time. An example of faster than real-time is analytic simulations that are used by the designer or test engineer to conduct trade-off or parametric analyses. A more detailed discussion of these types of simulations is covered in Section 3.1.

2.2. Brief History of Simulation

The use of mathematical models as a means to represent the aircraft first came into being with the advent of digital computers in the 1950's. After the sound barrier was broken, advances in aviation proceeded at an ever increasing pace. Engineers realized that they needed new tools to help them understand complicated aerodynamic phenomenon and to increase the safety of these hazardous test missions. A real-time simulation first appeared at the current National Aeronautics and Space Administration (NASA) Dryden Flight Research Center (DFRC) in 1957 with an analog simulation of the X-1B aircraft (Reference 2).

The first simulation at the United States Air Force Flight Test Center (AFFTC) was built in 1958 to support the testing of the X-2 aircraft. Shortly thereafter, NASA DFRC developed an X-15 simulator, which was the largest simulation then in existence. An exact duplication of the X-15 cockpit was developed as well as the use of the X-15 control cables and linkages, and aerodynamic surfaces. The simulator was used extensively to support test mission planning and emergency procedures training, as well as flight trajectory planning.

Early simulations had definite limitations because of the computer's inability to support complex, non-linear models. Still, these early simulations played a major simulation role until the advent of relatively inexpensive micro-computers in the 1970's. These computers greatly improved the ability to model the aircraft in such areas as high angle-of-attack (AOA), as well as complex flight control systems. Other types of simulations, such as in-flight simulation, made significant advances around this time period. The German Research Establishment, DLR, began using in-flight simulation in 1972 with their HFB320 aircraft to investigate digital flight control systems as well as defining steep landing approach patterns for noise abatement purposes.

Of course, with the advent of the personal computer (PC), a new wave of simulation advances has been made. Simulations that once required a room full of computers are now done on a PC at the engineer's desk. This has allowed simulation costs to be drastically reduced while at the same time increasing the utility of simulation. Still, each simulation requires an accurate representation of the aircraft and its aerodynamics, and this type of development work is required for each simulation no matter whether or not it resides on a mainframe computer or a PC. The test engineer should not be lulled into a false sense of security about the validity of the simulation simply because it sits on his desk instead of a lab. The test engineer still must understand the basic assumptions made in constructing the models and how the models were V&V'd, and then keep the simulation updated with real test data. The computer is a tool that can greatly assist the engineer, but it can never replace the important of role of applying sound engineering principles and good engineering judgment.

2.3. Benefits

Models and simulations that support flight testing do not just happen, instead they are the product of a long series of events that occur during aircraft development. As stated previously, the use of M&S to support T&E is just one of the ways simulations are used in the life cycle of the aircraft. The use of simulation to support flight testing is just the last stop in a long process. In order to get to that end point, the aircraft development programs must make a conscience effort to obtain the necessary data to build the models and a defined set of interfaces to allow the models to run together in a simulation. In the aircraft development industry, this has long been the standing practice, however, it was not always conducted with the same degree of fidelity and commitment. Recently, the Boeing Corporation in their 777 program has set a new standard for the use of simulation in whole product development cycle. From the outset of the 777 program, Boeing committed to making a "service ready" aircraft as soon as flight testing was completed. To accomplish this feat, Boeing made extensive use of M&S from the very beginning (Reference 3).

2.3.1. Cost

Certainly, one of the most noted factors in the defense of using simulation is the cost savings that can be realized. These cost savings can be elusive to document, and often hard to prove. This lack of firm proof will often lead an airplane development manager to question the cost of a high-fidelity simulation. However, consider the cost of a 777-200 aircraft in 1997 dollars ranged between $128M and $144M (Reference 4). The loss of this aircraft during flight testing would mean a significant financial loss for Boeing, not to mention the substantial delay in being able to sell the aircraft, which has direct impact on profit. A modern military aircraft may cost over $50M per copy, yet the flight test simulation generally costs an order of magnitude less to build and validate. The prevention of an accident in flight test often justifies the costs of a simulation.

Still, prevention is a cost avoided and not a cost saver. Reference 5 points out "That simulation offers the prospect of potential cost savings to be realized through reductions in development hardware, instrumentation, test facilities, and test programmes. By cost savings I do of course mean better value for money rather than simply reduced costs." This better value is obtained by being able to test more complex systems while still delivering to the customer a reliable assessment of the aircraft's flight characteristics and certification that the aircraft can be safely used by the customer. The Boeing 777 test program was able to lower costs by using the same data system in the simulator that was used aboard the test aircraft. In this way, the instrumentation and data system were shaken out before in-flight tests began. This increased the productivity of test flights especially early on in a test program. A recent United States spin test program was able to save $1M in reduction of test points due to the use of simulation. Much of the simulation work done in support of these tests was conducted on an engineering workstation co-located with the test engineers. The models needed to be high-fidelity in order to match the non-linear aerodynamics encountered at high AOA's. As discussed earlier, the advent of modern computers was a contributing factor to being able to conduct this type of complex simulation.

Still, cost savings as a result of using simulation are very elusive, and this sometimes increases the difficulty in convincing the aircraft developer of the need to build a flight test simulation located with or very near the test engineers. Simulation is a tool. Cost savings are indirectly realized because of the efficiencies resulting from using that tool. The United States Department of Defense (DoD) published a study examining the effectiveness of using M&S in the weapon system acquisition process. Included in this study was a particular examination of the costs either saved or avoided by using simulation in support of T&E (Reference 6). Once again, it proved difficult to gather direct quantitative evidence of the cost savings produced by using flight test simulation. Yet, there was a significant amount of cost avoidance realized by the test programs. It was only 40 years ago when simulation joined the tools employed by aircraft designers, and since then, aircraft flight testing safety has increased dramatically. This has enabled a rapid evolution of modern aircraft, especially in the military. Improving flight safety has always been the main of simulation. Cost savings or cost avoidance has been, and should continue to be, a secondary consideration when developing a flight test simulation.

2.3.2. Safety

By far the most significant benefit from using simulation to support flight testing is increased flight safety. Simulation allows the flight envelope to be investigated and understood prior to flight testing. Early use of simulation, even in the design stages can highlight safety concerns that can be designed out. Predictions of aircraft characteristics are gathered prior to testing and then used as a basis for comparison during actual testing. If significant excursions from predicted values occur during the tests, the test engineer is able to make an intelligent assessment as to whether to continue with the tests, or to quit and analyze the differences. Any of the simulations described in Section 3.0 are capable of generating data for comparison. Of course each simulation can be optimized to support a particular portion of the envelope expansion.

Maximizing the safety gained from simulation requires a disciplined process. The complete test team must be involved in gathering simulation data. A sufficient number of simulation runs must be accomplished in order to predict trends or find anomalous conditions. As mentioned earlier, a thorough understanding of the models being used is necessary in order to interpret the data. If anomalies are predicted, then the test team must seek to understand whether the model has been implemented correctly, or whether some assumptions were incorrect. If the model or implementation have caused a problem, then these must be fixed prior to continuing to gather data. Likewise, if the actual test data diverges from the predicted, the test team must endeavor to understand the causes. Once again, if the model is found to be incorrect, the test team must already have a plan in place to update the model. Occasionally this entails ceasing testing in certain portions of the flight envelope until the simulation is improved. This often causes a great amount of consternation within the program since the schedule may be impacted. This is why it is important to have an agreed to plan of action in place prior to flight testing. Making difficult decisions can be made easier if everyone agrees on the course of action when an in-flight anomaly occurs.

In Reference 7, Brain, Clayton, and Ward point out that the processes for using computer models in relation to flight safety is a major factor in correctly employing simulation. They assert that "The major problem of creating and using simulated 'virtual' aeroplanes for test and evaluation is that they require the same degree of investment, care and professionalism as any other aspect of aerospace test and evaluation. In this environment, modeling and simulation must be considered as high-integrity applications." A major point they make is that those involved in the T&E profession have yet to seriously address the processes used for simulation in support of flight testing. Building in a well thought out process from the earliest part of test planning will increase the likelihood of proper use of simulation data, and ultimately increase the safety associated with testing.

Gathering data is not the only way to increase flight safety using simulation. Proper coordination among test team members is also important. This type of training is best accomplished with the test pilot flying the test mission from the simulator and the ground test team monitoring the data in real-time. To maximize the effectiveness of this simulation it is important to replicate the test control room as realistically as possible. This includes the correct room layout and use of the same data displays. Reference 8 provides a detailed description of the use of simulators for training. One of the conclusions reached in the report is that "Flight simulators have proven to be effective training aids in nearly every test or application in a flying training program." The training benefits from using simulators can be further extended by integrating in the test team with pilot training.

Flight test history has shown that some test accidents and incidents may have been prevented had better coordination existed between the aircrew and the engineers on the ground. This type of training simulation allows the team to practice emerging situations and respond with pre-defined procedures as well as review procedures and practices that may occur infrequently in flight. Communications between the test conductor and the pilot can be rehearsed. This allows the pilot to know what "calls" the test conductor will make, and it ensures that communications between the ground and the air are kept to a minimum. These types of training sessions need to be conducted continuously during the test program, but they are especially important if there is a significant break in the test program, or a change in the test team. Further explanation of this type of testing, including scenarios and expectations are covered in Section 3.2.

Overall, increasing safety is one of the primary uses of flight test simulation. In the rush of getting the test program done, spending time on simulation often becomes a second priority. Yet the time and money invested are well spent is an accident or an incident can be avoided. The use of simulation to increase safety should be a part of every test program's safety reviews and safety planning. Experience has shown that senior test managers must insist that simulation is considered in the early stages of an aircraft development program. If simulations are not properly planned or budgeted for they cannot be used to increase safety later on in the program. This often requires a paradigm change on the part of the program manager, who is focused on cost, schedule and performance. It is the responsibility of the test community to educate and work with the program managers to insist that simulation is built into the program from the very beginning.

2.3.3. Life Cycle

The use of simulation not only benefits flight testing, but can play a major role in the life cycle of an aircraft. If the simulation is kept current during the test program and updated with actual test data, it will accurately represent the aircraft's characteristics. Simulations used for flight dynamics testing can be combined with other types of simulations such as avionics to form a more complete simulation of the weapon system and its associated subsystems. These simulations then form the basis from which future upgrades to the aircraft or its systems can be evaluated in virtual environment before deciding to proceed with development.

Once again Reference 5 points out, "Normal functions might include support of training, development of tactics, and evaluation of effectiveness." An example of this is how simulation is employed by the French at the flight test center, Centre D'Essais En Vol (CEV), located at Istres. Besides supporting flight testing in a cooperative effort with industry, the simulations are used for a variety of purposes including new concepts validation and software prototyping. They have employed piloted simulation to aid in the development of an Airborne Navigation Weapon System (Reference 9). CEV is able to use their simulators for multiple purposes because they have taken the effort to validate them in close coordination with industry.

Often the benefits of using the flight test simulation after the aircraft has been fielded are ignored, and the simulations become unusable after a period of time. For example, changes made to the aircraft, flight controls, or systems are made without corresponding changes to the models. Furthermore, past experience has shown that major upgrades to an aircraft many years into operation often result in having to rebuild flight test simulations since they have been dismantled or badly out of date. Once again it is up to the flight test managers to work in partnership with the development program managers to ensure there is a plan that will utilize the investment made in developing a flight test simulation capability. These simulations should be viewed as assets in the aircraft program and not just as one time occurrences that are only good for flight testing.

Overall, there are many benefits from using simulation to support flight testing. This section has tried to provide a cursory overview of some of those benefits such as cost, increased safety and life cycle support. These benefits can only be fully realized if there are sufficient processes in place that will govern the use and validation of the simulations. It is incumbent upon the senior test managers to work closely with the aircraft developers to insure that these processes are identified and adhered to during the test program. Only when this partnership is developed and strengthened over the life cycle of the aircraft, will the true benefits of using simulation become apparent.

3. TYPES OF SIMULATIONS

As mentioned earlier, five types of simulations will be discussed in detail in this document. Each of these simulations is used to support flight testing, however some are better suited to some tests than others. Section 5 discusses the uses of simulations, but to understand the uses requires a thorough knowledge of the simulation. Figure 3-1 correlates these together in a matrix. Clearly, a simulation can support multiple test objectives. It is incumbent upon the test engineer to understand the strengths and weaknesses of each type of simulation in order to determine the optimal tool to apply to the test.

Recall that a simulation was defined as a method for implementing a model over time. Many different models make up a simulation. No matter the type of simulation, the models must be matched in both fidelity and timing so that the complete set can be correctly executed in a simulation. Understanding the level of fidelity of the models used in the simulation is critical to comprehending the meaning of the results. It is akin to understanding the how the number of significant digits used in a multiplication problem will affect the accuracy of the answer. This applies to models in a simulation. The result of a simulation is only as accurate as the lowest fidelity model used. It therefore does not make sense to use a high fidelity model coupled with a crude low fidelity representation. Once again, it is the responsibility of the test engineer to understand the deficiencies in the models being employed in the simulation. A complete description of models and issues such as model fidelity is provided in

Section 4.

Obviously there are a lot of factors to consider when building a simulation. Defining the requirements for the simulation is the first step. During requirements definition, the test team must decide how they plan to V&V the simulation. When building the flight test plan, the test team needs to consider the test points required to V&V the simulation. This should be closely tied to the requirements for the simulation. For example, if a simulation is required to support high angle-of-attack (AOA) tests, then the test plan should contain structured tests that will allow the data to be used in validating the simulation. Appropriate time must be built into the testing to allow for data reduction and simulation validation.

The issue of simulation validity is an important aspect if the benefits of using simulation are to be realized. Section 4.6 contains a complete description of V&V including definitions and additional detail on procedures and practices. Reference 10 has an in-depth discussion of simulation validation as it applies to aircraft and subsystem certification. An important point made in the reference states: "Thus acceptance authorities and manufacturers need to justify confidence in simulation results from either relevant flight test validation or from an identification and acceptance of the validity of the simulation system design methods applied to the specific simulation."

The following sections delve into the details and considerations associated with each type of simulation. These sections are meant to be general guidelines and are not absolutes because exceptions will always exist. Construction and validation of each type of simulation brings unique challenges that must be overcome on a test program to test program basis.

3.1. Analytic (Non Real-Time)

Analytic simulations are non real-time simulations that are used to conduct a multitude of engineering tasks including design tradeoffs, system performance characterization, operational limitations, safety analysis, test planning, and test predictions. Recall that non real-time was defined as simulated time that does not operate at the same rate as actual time, either faster or slower than real-time. Thus one second of "clock-on-the-wall time" may take ten seconds of computational time. It is not important to synchronize with real-time because these simulations act in a stand-alone fashion and do not interface with humans or actual hardware. However, there is no restriction from making analytic simulations run at the same rate as actual time. An example of this is having analytic simulations run in the test control room synchronized to actual test data being telemetered down from the test aircraft. To accomplish this often requires optimization of the simulation so that it can be synchronized with the test control room telemetry data and associated hardware.

In general, the hallmark of analytic simulations is that they run very high fidelity models. These models are typically developed during the aircraft design process. The models are the most accurate representation of the system being developed and tested. These models may have been derived from Computer Aided Design (CAD) drawings in order to support structures analysis, or very fine grids for Computational Fluid Dynamics (CFD) analysis of the aircraft's wing or engine characteristics. The complexity of the models, along with the focused nature of the analysis is the primary reason why the simulations often do not run in real-time. Aircraft designers and manufacturers may have dozens of simulations tailored to support a particular aspect of the design process. The engineers will make thousands of simulation runs looking at various characteristics of the system and optimizing design features.

3.1.1. Intended Use

Analytic simulations play an important role in flight testing but they are best used for test planning, and test maneuver definition. Essentially these simulations enable the test engineer to investigate flight test issues early on in the development of the aircraft. The main challenge facing the engineers is to work with the various design engineers to develop a simulation that has appropriately matched fidelity models. It makes little sense to have a high fidelity aerodynamic model matched with only an approximation of the flight control system characteristics. But this is where understanding the intended use becomes important.

An application of the analytical simulation is in the planning of in-flight structures testing. This type of simulation requires a detailed representation of the aircraft's structural response to an input, along with models that may influence or excite the structural response. Typically these high fidelity ancillary models are limited to aerodynamics, flight controls, and equations-of-motion models. Aircraft components such as the engine are generally modeled with lower fidelity considerations such as mass and weight. Conversely, for high AOA test planning, it may be important to have an extremely high fidelity model of the engine so as to account for gyroscopic or thrust effects. Most test engineers working in conjunction with the appropriate discipline engineers can make a reasonable estimate as to the appropriate fidelity of the required models. Still, secondary considerations such as run time, program size, affect the decisions as to the fidelity of the models.

Simulation runs to explore the potential matrix of test points can best use the power of analytic simulations. The test engineer can then plot out the results of the runs in order to visualize the potential flight envelope. This enables the engineer to look for areas of non-linearities or inconsistencies. These interest areas can then serve as the basis for early flight test plans and safety-of-flight planning exercises.

3.1.2. Resources Required

The main focus of an analytic simulation is the detailed software models that can be developed to represent all aspects of the system. Since run time is not a major consideration, there do not have to be compromises made in the fidelity of the models. This is especially true for the aerodynamic model. The aero model, which is developed from wind tunnel data, can be hundreds of thousands of points. Analytic simulations enable the whole model to be put into the simulation. This is important to facilitate complete exploration of the interactions of the aircraft aerodynamics and flight control system. This is also true for other disciplines such as flutter and structures. These simulations are often complex and the ability to predict aircraft flutter and structure characteristics in enhanced by a complete aero model. This is contrasted to a real-time simulation, which must often scale back the aero model in order to make it fit the frame time of the simulations. This will be discussed in more detail in the next section.

The computer resources required are a trade-off between cost and simulation performance. The faster the computer, the more simulation runs that can be made in less time; however the faster the computer, the more expensive it is. Complex models often require significant disk space and memory, and so the engineering team often must have high-powered computers. This is coupled with the need to visualize the results of the simulation runs. Modern visualization tools can take the results of the simulations and produce detailed graphs automatically. Furthermore, the data can sometimes be used to drive an animation of the aircraft so that the engineers can observe how the aircraft behaves in certain situations like high AOA's or spins. Complex visualization tools require expensive graphical devices and drive the cost of the machine up. Obviously, the benefit of these visualization tools must be weighed against the cost of the software and hardware.

Once the design phases of the project have been completed and the full aircraft envelope has been simulated, the requirement for very high-fidelity aerodynamic models may be reduced. During the flight test program, the engineering team may decide they need an on-sight analytic simulation to support flight testing. With tight flight test budgets, high-end workstations may not be affordable, but personal computers (PC) may be an alternative computing platform. To fit within the constraints of PC, only portions of the models may have to be hosted, or the models may need to be scaled down. For example, if an area of concern is identified, only that area of the aerodynamics model may be hosted on the PC. A thorough understanding of the limitations of the models is necessary if they are to be used correctly to support testing.

Thus, with these analytic simulations, it becomes a trade-off between cost and performance based on intended use. As PCs become more capable for less money, these tradeoffs may become a thing of the past. What is important, is up-front planning on the use of analytic simulations and a complete understanding of the complexity or assumptions made in the models used in the simulations.

3.2. Engineering or Man-in-the-Loop (Real-Time)

Engineering or Man-in-the-loop (MITL) simulations are the most common types of simulations used to support flight dynamics testing. Most aircraft manufacturer and flight test installation has access to MITL simulations. These simulations provide the most benefit to the test team and are used in virtually every application support flight testing (See Figure 3.1). However, putting together a high fidelity MITL simulation is expensive and requires significant expertise. Factors that must be considered are run time, model complexity, fidelity of the cockpit, fidelity of the motion base, degrees of freedom, and the visual scene, and location of the simulation. All of these factors must be considered based on the intended use of the simulation and its relation to the execution of the flight test program.

MITL simulations have a broad spectrum of use in the aerospace industry. They play a key role in virtually every facet of a weapon systems life cycle. They are used for concept development, system requirements development, design tradeoffs, design testing, human factors testing, flight testing, operational planning and operational testing, system training, and system upgrades. MITL simulators play an important role in the certification of commercial aircraft as well as in the training of commercial pilots.

In general, MITL simulators, whether supporting design or testing, consist of the same three basic components: tactile, visual, and mathematical. The tactile refers to the pilot's control of the aircraft such as the stick and the throttle. The visual refers to the visual information presented to the pilot including cockpit displays and out-the-window (OTW) visual scenes. Mathematical refers to the validity of the models being used in the simulation to include aircraft, environment and even the visual scene models. Each of these components have varying degrees of fidelity depending on the required use of the MITL simulation. For example, to run a human factor's test on the quality of information displayed on a cockpit Multi-Function Display (MFD), does not necessarily require a high-fidelity OTW scene. In fact, the presence of an OTW scene, may distract the pilot's attention from focusing on evaluating the MFD. Thus, MITL simulators are often tailored to meet a specific need.

There are instances where all three components are used at the highest possible fidelity. For example, the Dutch National Simulation Facility (NSF) at the National Aerospace Laboratory of the Netherlands, NLR, uses the highest possible fidelity of tactile, visual and mathematical components. Another such facility is the Air Combat Environment Tactical Evaluation Facility (ACETEF) located at Patuxent River Naval Base in the United States. These facilities use actual cockpits, 360-degree visual systems, and high fidelity mathematical models. Even still, there remains considerable debate as to how much of each component is "good enough". Once again it comes back to the task the pilot is being asked to perform. Understanding the intended use of a MITL simulator is absolutely necessary to insure that the components are at the appropriate level of fidelity and that the money spent justifies the expected results. The areas of intended use and simulation components are covered in more detail in the next two sections.

3.2.1. Intended Use

For flight test purposes, MITL simulations are best used for test planning/envelope clearance, test maneuver definition, flight test anomaly investigation, test scenario development and flight crew training. The following sections are intended to give the reader a general overview of how MITL simulators are employed for each application.

3.2.1.1. Test Planning/Envelope Clearance

Perhaps one of the most important benefits of using manned flight simulation is the increase in flight test safety. Since the early years of simulation in the 1950's, manned simulation has provided the pilot and the engineers an opportunity to understand the flight characteristics of the aircraft before flying it. Data gathered from piloted simulations can be evaluated to determine if any unsafe conditions may occur during normal or test flying. Further, this data lays the foundation for the systematic expansion of the aircraft's flight envelope. The methodology for evaluating the safe handling characteristics of an aircraft varies however, known areas of concern are typically evaluated first. For example, the takeoff and landing characteristics are usually the first area to undergo a thorough examination of the aircraft's handling qualities. Numerous takeoff variations across a multiple of aircraft gross weights and centers-of-gravity can be quickly conducted and evaluated using MITL simulations. These analyses may occur early on in the design phase to help tune the flight control system gains or help adjust the stick forces during aircraft rotation. But most importantly, the design team is searching for anomalies that may cause an aircraft accident such as a Pilot Induced Oscillation.

During a high-speed taxi test on the YF-16, the pilot encountered an unexpected roll oscillation. As taxi speed of the aircraft increased the pilot applied roll stick control to keep the wings leveled. As he did so he found that the roll axis was too sensitive and he induced a roll oscillation. To regain control of the aircraft, the pilot applied power and took off. The subsequent investigation uncovered that the roll axis gains were set too high in the landing configuration. The aircraft flight control gains had been tuned in a MITL simulator. To optimize roll performance, the roll gains were set as high as possible. The lack of physical cues in the simulator resulted in the control law gains being set too high. During the taxi test when the physical cues were being fed back to the pilot, he found that the aircraft was too responsive in roll thereby inducing the oscillation.

The MITL simulator is an ideal tool to insure that the aircraft will perform as expected, but optimization of the control laws cannot rely solely on a MITL simulation. The lack of physical cues during closed-loop maneuvering must be considered when viewing the results of a MITL simulation. Improvements in the visual scene will help this, but not completely cure the phenomenon.

The same applies to the landing configurations. Simulator tests may be done to determine if the pilot has sufficient control authority to overcome a crosswind or determine the proper AOA for landing with a heavy airplane and an aft center-of-gravity. Modern digital control systems often switch flight control modes when weight is placed on the aircraft's wheels during landing, simulator tests are conducted to determine what, if any, transients will happen and to insure the aircraft can properly transition between flight control modes. Numerous other types of tests are done using piloted simulation to completely investigate the gamut of takeoff and landing configurations.

Similar types of investigations are conducted in other regimes of the flight envelope such as high AOA and transonic maneuvering. The test engineer and test pilot often work together in the simulator to develop techniques for recovery from out of control flight conditions that may result from aircraft stalls or high AOA maneuvering. They will look at the aircraft's spin characteristics as well as the cockpit's displays to insure that the pilot has the proper information presented to recover from an out of control condition. However, the significant limiting factor in using MITL simulation for these kinds of investigations is the quality of the aerodynamic data within the simulation. Very often the data at high AOAs is non-linear and not easily measured with wind tunnel testing or CFD. Drop models of the aircraft may be used to gather data relating to the aircraft's spin characteristics. This data is then used to refine the quality of the simulation. Still, for high AOA testing flight testing is required to determine the aircraft's flight characteristics. Data gathered from simulations is critical when doing these kind of hazardous flight tests. Not only does the simulator provide the pilot with a familiarity of the aircraft's handling characteristics at high AOA, but it also provides the engineer with data to measure flight test against. That is, the test engineer will gather data on critical parameters such as maximum AOA or pitch angle achieved during a particular test maneuver. This data will be plotted and used as the starting point for comparison against actual aircraft performance. As the flight envelope is expanded at subsequent higher AOAs, actual aircraft data will be plotted against predicted. If there is significant deviation from the predicted, the tests will stopped until the difference can be explained and the safety of the aircraft is assured the next time the pilots flies it in those regimes. This methodology of comparing actual data against the simulator greatly increases the flight safety and provides confidence in the validity of the simulation. Further, if the actual data consistently matches the predictions from the simulation, then the pace of the flight tests may be increased by eliminating aircraft test points. However, before any test points are eliminated, the whole test team must feel confident that the simulator accurately represents the aircraft's characteristics. In non-linear regions such as high AOA, end points should always be tested to insure that the aircraft can actually achieve the conditions it was designed to operate in. The test team should never eliminate those critical end points on the basis of simulation, however, intermediate or build up test points may be eliminated after careful consideration.

Using a MITL simulator cannot guarantee that there will be no aircraft anomalies, but it does reduce the risk associated with flight dynamic's envelope expansion. Other aircraft envelope expansion tests such as flutter and structures still require rigorous flight testing to insure that the flight envelope is expanded to the design requirements. However, a MITL simulator can be used to help define the type of flutter maneuver to be accomplished and provides the pilot an opportunity to practice the maneuver prior to flying. This is covered in more detail in the next section.

3.2.1.2. Test Maneuver Definition

The techniques and flight maneuvers used in flight dynamics testing are well known and have been refined over the years. However, each unique aircraft with its unique flying qualities requires that each flight test maneuver be precisely defined to insure that the flight conditions can be achieved and that the maneuver is repeatable. In addition, the sequence of conducting the maneuvers often depends on other factors such as integration with other test disciplines, length of the projected test sortie, and if any anomalies are expected during the tests. Very often, the test pilots may need to learn the proper technique for entering a maneuver so as to precisely obtain the flight test conditions. This kind of maneuver definition/refinement can be accomplished in flight but it is better suited for a MITL simulator.

For example, the test may call for execution of a constant "g" turn while maintaining the target airspeed. In order to execute this maneuver properly and to minimize any repeats while flying, the pilot will need to practice this test so as to understand the proper setting throttle, the rate to apply pitch stick force. Repeated practice of the maneuver will insure that the pilot can execute it properly in the air. It also allows the pilot to see the results before flying. As a side benefit, the test team gains an understanding of any problems that may arise if the pilot does not precisely hit the test conditions.

The test program for the Fokker 60 (F60) aircraft is a good example of how a MITL simulation can be used. One of the conditions the F60 was required to demonstrate was being able to maintain positive stick force at 0 g's when icing is present on the horizontal tail. This test was considered to be a hazardous test and so the test team used a MITL simulator to mitigate the risk. The simulator was used to establish a build up methodology to get to the 0 g flight condition. It was also used to determine the test technique required to reach the particular flight condition. The test team also used the simulator to develop and practice departure and recovery techniques just in case they encountered an unpredicted anomaly. This allowed for a reduced flight test program, which reduced the risk of the test program.

By using a MITL simulator, the F60 test team was able to scale back the flight test program and thereby reduce the risk of the test program. Actual F60 flight tests showed that the aircraft flew better than predicted in the simulator, but the change is stick force was the same in the aircraft as in the simulator. The use of the MITL simulator on the F60 test program was invaluable tool and an integral part of their successful flight test program.

Another common use of a MITL simulator for test maneuver definition is for edge of the flight envelope tests such as high AOA or high-g maneuvers. However, the MITL can also be used to refine closed-loop test maneuvers such as Handling Qualities During Tracking (HQDT) tests. To properly evaluate closed loop characteristics in a simulator requires a very good to excellent out-the-window visual scene. It must include a good target model, a high-fidelity cockpit with the proper stick forces and engine models, as well as a clearly defined task so that the pilot can evaluate the results he is seeing in the simulator. The object of using the MITL simulator is to determine optimum starting conditions and flight conditions that may have the potential for some problems. It also gives the pilot an opportunity to evaluate and understand the avionics and how they perform so they do not detract from the pilot's in-flight evaluation. A word of caution must be noted here. If the simulator does not have the required fidelity as discussed above, then the closed loop handling qualities evaluation in the simulator may have detrimental effects and bias the pilot's in-flight evaluation. Also missing from the evaluation in the simulator are other tactile cues such as motion and sound. The flight test engineer and test pilot must take all of these facets into consideration when deciding how to use the MITL for closed loop maneuver definition. Thus the use of a MITL simulator to obtain Handling Qualities Ratings must be used with caution and the full awareness of the limitations associated with a MITL simulator.

3.2.1.3. Flight Test Anomaly Investigation

Another significant use of MITL simulations is flight test anomaly investigation. Often, if a problem is encountered in flight, the MITL simulator provides an excellent tool to try and duplicate the anomaly. Flight dynamics' anomalies can range from minor, such as roll rate too high, to catastrophic, such as a departure or some other out-of-control situation. For the purposes of this report, an anomaly is a deviation from the expected. As stated earlier, the flight test engineer typically has done some simulation studies and has an expectation of what will occur during the tests. If the aircraft deviates from these predictions, the test or design team should investigate the cause of these deviations.

A method for doing this, is to have the same pilot fly the same maneuver over in the simulator. Exact flight conditions need to be duplicated and pilot inputs must be the same. Using the MITL further allows the test team to evaluate the sensitivity of the anomaly around the area of concern. In this manner, the test team can decide if they are approaching a potentially hazardous part of the envelope that they had not been previously aware of. However another method for duplicating the anomaly is to take the actual flight data and play it back into the simulator. This will allow for the exact duplication of all flight conditions and pilot inputs, and thus there will be no questions regarding the input that caused the dynamic anomaly. This can only be accomplished if the simulator is capable of reading the recorded data format and all of the parameters are identical. This is another factor to consider when designing and building the simulator. If a match between the actual flight anomaly and the simulator cannot be obtained even with actual flight test data, then the simulator validation must be questioned. The aerodynamics, flight controls, or even a software coding error could contribute to the differences between flight test and simulator.

Using the MITL to duplicate an anomaly used to be the only method available to the test team. The primary drawback to this method is that it must be done after the airplane has landed, and it knowledge of the exact flight conditions during the anomaly. This can delay the test program. To overcome this, simulations are being used during the actual test mission. In support of the EuroFighter (EF) 2000 program, British Aerospace developed a capability called "Reprediction". This is completely documented in (Reference 11). The reprediction capability takes actual flight test data and inputs it into a simulation running during the actual test mission. In this fashion, the test team is able to determine how close the actual test maneuver compares with the simulation. They are able to rapidly assess any differences from pre-flight predictions that may be as a result of pilot input or flight conditions. This allows continuation of the test mission despite anomalies from the predicted aircraft dynamics. Reprediction has been very successful in supported the EF2000 test program. Another similar capability was used by NASA to support the X-29 test program (Reference 12). Once again, this real-time simulation capability played an important role in keeping the test program moving along when differences between predictions and actual test data occurred during testing.

3.2.1.4. Test Scenario Development

An important use of MITL simulators is to actually develop the test profiles to be used during flight testing. Certainly one of the goals of the test team is to maximize the data gathered during any particular flight. Optimizing test maneuvers and test profiles is best accomplished with a MITL simulator. Before doing this, the test team must determine if there is a critical order in which test points must be conducted. That is, test points at a certain altitude or airspeed must come prior to test points in other parts of the envelope. Factored into this consideration must also be the requirements of other test disciplines. Flutter and structures test points often proceed before many flight dynamics test points once a sufficient flight envelope has been cleared.

Once the order of the testing has been worked out, the simulator can be used to optimize the flight profile. A high fidelity simulator that accurately models the actual airspace and aircraft functions such as fuel flow and fuel burn is essential to optimizing the flight profiles.

3.2.1.5. Flight Crew Training

As stated previously, edge-of-the-envelope flight testing requires precise maneuvering and often results in a loss of the aircraft's energy. High AOA and very slow speed maneuvers such as stall testing can lead to departures from controlled flight and so must be carefully entered by the pilot. At the U.S. Air Force Flight Test Center at Edwards Air Force Base, these kind of tests maneuvers are conducted in a piece of controlled airspace called the "Spin Area". The spin area consists of a cylinder of airspace that is off limits to other aircraft when tests are being conducted, and the ground in the area is uninhabited in case of an aircraft accident. Once in the spin area, the pilot is cleared to execute the test maneuver. The maneuver(s) must be completed prior to exiting the spin area. To maximize the test time, as many maneuvers as possible are attempted while in the area. Once out of the area, the pilot flies a racetrack pattern around to enter again from the other side. Inefficiencies in this process can cost the program time and money.

To help avoid these inefficiencies, the pilots need to be familiar with the techniques required to properly enter the test maneuver. One way to optimize the techniques and train the pilots is by using a MITL simulator. To enhance the training and to plan the actual flights, it is preferable to have the test area modeled and presented visually to the pilots. The simulator training should be conducted as if they were doing an actual test flight. This gives the pilot a sense of timing and an understanding of how rapidly he must accomplish the tests before exiting the controlled airspace area. This also allows the test team to piece together the most efficient series of tests so as to maximize the number of test points actually accomplished in the controlled airspace. Further, it helps everyone realize that some types of test maneuvers may not be able to be accomplished in that defined space and must be reconsidered. For example, a slow deceleration until maximum AOA is achieved may take more airspace than allotted. To remedy that, a slower entrance speed may be picked or the deceleration should begun before entering the test area.

What is important to remember is that a more realistic simulation environment contributes to effective training. Not only is the test team looking for data to compare with flight tests but also the pilot is receiving valuable training. Part of the idea is to put the whole test team under the stresses they will encounter when performing the tests. The introduction of constraints such as time and airspace increases the pilot's workload and that may lead to mistakes during these hazardous maneuvers. A mistake may lead to an aircraft departure or similar condition. It is obviously best to find these potential problems in the simulator instead of in the air. The same goes for the test team monitoring the data on the ground. If key members of the team are required to make critical safety-of-flight decisions, stressing those members with additional information may point out processes or data presentations that may need to be improved. To obtain maximum benefit from a MITL simulator, creating a realistic test environment for the pilot and the test team is imperative and critical to mitigate any safety risks.

Another important training technique associated with MITL simulators is flight control system failure training. Most new aircraft have a digital fly-by-wire flight control system. Many have adaptive control systems that change depending on the aircraft's current state such as in the landing mode. These control systems are software intensive systems and as such they are prone to nuisance or catastrophic failures. Early on in the development of a new control system, it is imperative that the pilot and test engineering support team be trained on how to react to these control system anomalies. Testing of these failures is often called Failure Modes Effects Testing (FMET). These tests will covered in detail in the Hardware-in-the-Loop section. However, the pilot and crew must be trained to react to these failures. The pilot must be aware of any adverse aircraft motion that may occur due to a flight control system failure. These failures and their associated transients, if any, need to be examined at all corners of the flight envelope.

MITL simulators are ideally suited for this kind of training, however it does require an actual flight control system computer to properly accomplish this training. This training can be accomplished in two ways: first, with the pilot expecting the failure and then observing the reaction of the aircraft including the caution and warning lights; second as a surprise during some critical maneuver. The first method is best used to familiarize the pilot with the particular failure modes and to let him step through the checklist to reset the failure. This is very similar to the emergency procedures training that pilots typically receive on a recurring basis. However, inducing failures during critical test maneuvers has the greatest training potential. The test team is able to evaluate the pilot's reaction to the failures and to determine if unexpected pilot inputs could cause further degradation of the flight control system. For example, introducing an AOA failure during the middle of a high AOA test maneuver trains the test pilot on how to react and also evaluates the recovery techniques used by the pilot. The real strength of using a MITL simulator is the easy ability to duplicate the tests so that the pilot and test team can completely evaluate the situation and optimize the recovery techniques.

An end product from this simulator work should be additions to the flight manual or flight limitations that have to be cleared during the flight test program. Since flight control system failures are not usually induced during flight testing, the techniques and procedures developed in the simulator may be the only information available to the test pilot or the pilot that has to fly the aircraft when it is eventually fielded. In this capacity the MITL simulator plays a key role in the whole life cycle of the aircraft.

3.2.2. Resources Required

MITL simulators are fairly complex and costly to develop and maintain. Although the cost of computer hardware continues to decrease as capabilities increase. Still the basic hardware and software components required for a MITL simulator are: a high performance computer system often with multiple processors with a real-time computer operating system that allows for deterministic time management; a high-fidelity cockpit with real aircraft stick and throttles (if possible); an out-the-window (OTW) visual scene; data analysis/data visualization tools, and possibly a motion base.

The use of a motion base simulator must be considered very carefully. A significant amount of research has been conducted regarding the utility of motion base simulators. This report will not delve into the various aspects of motion base. Generally, motion base is useful when performing maneuvers that have limited accelerations and limited angular displacements. For example, landing tasks and aerial refueling tasks can be done using a motion based simulator. However, maneuvers like stalls and spins should not be conducted in a motion base. If interested, the reader is encouraged to explore the literature available regarding the use of motion based simulators.

Each of the components listed above is critical to being able to run a MITL simulation. The first component provides the basic platform and is often the most expensive. The cost for a high performance computer has decreased dramatically over the years, but the software required to run models in real-time becomes the most costly and complex item. The computers must have a deterministic real-time operating system. The key piece of software that runs on the system is a real-time executive. This executive schedules functions, keeps track of frame times, allocates processor resources, distributes data, and executes the models within the simulation. The executive software is essentially the heart of the simulation system. Typically once a simulation facility develops an executive the models and other software components are developed to work with the executive. There is no common simulation executive among contractors or countries. Each facility has developed their unique executive over the lifetime of the simulator. However, there are many commercial companies that have developed simulation executives and can readily construct new ones.

From the viewpoint of the pilot, the most critical piece of a MITL simulation is the cockpit. The fidelity of the cockpit varies greatly depending on the application. Low fidelity cockpits may only have the aircraft's stick, throttle, and rudder pedals as well as few gauges such as airspeed, altitude, Mach Number, etc. These cockpits are geared towards engineering analysis and have no utility to training. Whereas a high fidelity cockpit may be duplicative of the real cockpit all the way down to the exact instruments and avionics displays. These cockpits are best suited for all MITL tasks including pilot training. They are essential if failure mode analysis is to be performed. However, to obtain a duplicate of the aircraft's real cockpit can be very expensive and impractical if the program does not have sufficient quantities of some cockpit items.

The OTW visual scene is also required for pilot-in-the loop evaluations. Visual scene fidelity varies greatly depending on the task. A lengthy discussion on this topic is covered in section 4.4. At a bare minimum, the visual scene must have an horizon line and some way of telling sky from the ground. For up and away maneuvering it often does not matter what level of fidelity of the visual scene since the pilot typically sees only the sky. There are those conditions such as an out-of-control spin that requires the pilot to have as much situational awareness in the simulator as possible. Landmark features on the ground are required if the pilot is to practice test maneuver setup and execution. The higher the fidelity of the visual scene the more immersed in the simulation the pilot will become. Building and creating OTW visual scenes is a difficult and time-consuming process. There are simulation companies that will build these visual scenes or there are commercial tools available to build the visual scene in-house. Either way, the scene must reflect the kind of tasks required by the simulator. A mismatch between the visual scene and the task being given to the pilot and the confidence in the simulator data results can be called into question.

This leads to the last key element data analysis/data visualization tools. In order for the MITL to be effective, the engineering team must have the correct tools to analyze and/or visualize the data. These can be commercial tools that are integrated into the system, or they can be developed specifically for the simulation. Ideally, the analysis tools used in the simulator would be the same as those used to analyze flight test data. This includes real-time simulation monitoring as well as post-simulation data analysis. Common displays and tools provide an enhanced learning environment for the whole test team and allows them to "tweak" their displays and analysis routines before flying.

Overall the development of a MITL simulator is very complex and is best left to those people who have such skills or knowledge. Each of the flight test centers visited in preparation for this report had an in-house team of experts developing their MITL simulations. This team was a mix of government employees and contractors. Developing and maintaining a simulation team is critical for the long term success of a MITL simulator.

3.3. Hardware-in-the-Loop

Hardware-in-the-loop (HWIL) simulations take MITL simulations one step further. Instead of computers running digital models of the aircraft, the aircraft's avionics, flight control system, and maybe the engine, the actual components are laid out and connected on a spreadbench. The most important component of a HWIL simulation is the flight control system. Up to this point the simulations have been representations of the flight control system. When the hardware components are added to a digital simulation they introduce an added element of time delay that could potentially have adverse affects on the aircraft flight dynamic performance. The sensors that provide inputs into the flight control system, for example airspeed, altitude, AOA, must still be modeled. However, the effects of sensor errors can be evaluated now that the actual flight control system is in the loop. Ideally, a HWIL simulation will use an actual cockpit mockup including the actual cockpit displays and instruments. This is especially critical in order to evaluate the complete closed-loop system effects with the pilot-in-the-loop. The NASA sponsored F-18 High Angle-of-Attack Research Vehicle (HARV) made extensive use of the HWIL simulation (Reference 13). For this research test program, it was the most frequently used simulation configuration. The simulation was used for pilot training, flight test planning, FMET, and flight control law validation. The last two comprised the majority of the uses. In this simulation the actuators were modeled using analog models. This further improved the fidelity of the simulation.

A factor that must be considered when building a HWIL simulation is the synchronization between the actual hardware (the flight control computer) and the digital models. The computer models must execute in time to supply and receive data from the actual hardware. This means that if a digital flight control system is operating at 50 Hertz (Hz), that is 50 frames per second, then the models must also execute at 50Hz or a factor of 50. For example, it may not be necessary to execute the aerodynamic model 50 times per second so it could be run 25 or even 5 times per second. Likewise, a digital engine controller model may need to run faster than the flight control system, so it could execute at 100 times per second. What is critical is that at the end of the major frame (1 second) all of the computer models must have finished executing and the data must be available to be transmitted to the flight control system hardware. This is truly a real-time system.

There are many schemes to insure the synchronization between the components. For the X-31 program, NASA Dryden made a minor change to the flight control computer's software. A discrete output from the computer was used to provide a synchronization pulse to the simulation system. The flight control computer software was modified to set the synchronization discrete true immediately following the flight control computer clock interrupt. The discrete was reset immediately after the control law calculations were made in the flight control computer.

Next, the latency between the flight control system and the simulation computers must be kept to a minimum. Ideally, the data transmission time would be identical to that of the actual aircraft. Typically the flight control system receives analog data, so the output of the simulation computers must first be converted over to an analog signal and then transmitted across to the hardware. This whole process of taking the computer output, converting it to an analog signal, transmitting it over to the hardware must be precisely synchronized or else the simulation results will be skewed and therefore not match the actual aircraft.

It is incumbent upon the simulation engineer to work with the appropriate discipline engineers to create models that will run in the allotted timeframe. If all of the models cannot be executed at the same rates, then the engineering team must identify which models can be slowed down without loosing any fidelity. Timing tests must be conducted to validate that the timing and synchronization between the flight hardware and the simulation computers accurately represents the intended aircraft design and implementation. Once the full simulation has been validated, then it can be used for any number of simulation tests.

3.3.1 Intended Use

The primary uses of HWIL simulations are for pilot training, flight control system software validation, and FMET. Because actual aircraft flight hardware is used, it is important to focus the simulation tests that can only be accomplished using the actual hardware. For new flight control systems, the computers used for the first flight are often taken directly out of the simulation laboratory. In this way, the aircraft developer can be assured that the system has been tested as thoroughly as possible.

For the F-15 Short Takeoff and Landing (STOL) Maneuver Technology Demonstration (MTD) program, a HWIL manned flight simulator was used to verify hardware and software interfaces, confirm proper implementation of the flight control laws, verify failure transient suppression and degraded mode flying qualities, and provide pilot training (Reference 14). For this particular application, the actual hardware used included the flight control computers as well as several key avionics components including the actual Heads-up Display (HUD).

Once again, the more realistic the cockpit the more relevant the training will be for the pilot. The training is intended to give the pilot an opportunity to observe and react to actual flight control system failures and to reset those failures. As stated earlier, these failures can be induced during a static condition or during dynamic maneuvering. Inserting failures during maneuvering allows the pilot and the test team to develop procedures to safely recover the aircraft from a hazardous situation. It also gives the pilot an opportunity to observe the magnitude of transients that may occur as a result of a flight control system failure. Ideally, the control law design team will have endeavored to minimize any transients as a result of control system failures.

These kind of tests cross over the boundary to FMET. By running failure modes and effects tests on the actual hardware, the design team can work out and undesirable characteristics brought on by failures. These tests are typically conducted without a pilot and they are primarily designed for the engineering team's use. Sometimes a separate set of engineers will be used to design the FMET tests. They will examine all of the control law design documentation, software design, as well as the hardware design, looking for "sneak circuits" or other potential ways to make the system fail. The FMET test matrix may call for multiple failures to occur at the same time or to have those failures strategically placed to create the greatest data latency problems. It is the FMET team's job to try and anticipate the unexpected and determine if the aircraft's response is safe or if the control laws need to be modified

Given that the flight control computer is a flight critical component, it is essential that the control law software be fully validated prior to first flight. The validation process consists of measuring the system response at numerous points across the flight envelope, and then comparing against the expected responses. Typically, the expected responses were generated from other computer models, usually executed in a non real-time simulation. The validation process insures that the flight control laws were properly implemented in the flight control computer and that they still perform in an integrated system. Still, the final validation of the flight control system software can only occur on the aircraft once the hardware is installed and connected to all of the aircraft sensors. Thus, even after extensive HWIL simulation tests, additional tests are required on board the aircraft. Not only do these tests validate the flight control software, but they also validate the accuracy of the HWIL simulation.

3.3.2 Resources Required

The resources required to conduct HWIL simulations are similar to those for the MITL simulations. The significant difference is the addition of the actual flight control computer and any other interface or avionics equipment required conducting the simulation. As mentioned previously, great care must be taken to properly represent the data latencies that would be found on board the aircraft. Special interfaces may need to be developed in order to inject failures into the system. For example, if AOA is a sensor input into the flight control system, then the AOA signal generated from the output of the simulation, must be interrupted and possibly modified. Minor non-intrusive modifications of the actual flight control system software may be required in order to insure synchronization between the computer simulation and the flight control computer.

Another important resource to conduct these HWIL simulations is the ability to access and record any memory location within the flight control computer. This is essential for FMET and software validation tests. This allows the response of internal flight control system software parameters to be recorded and compared to expected results. This kind of instrumentation needs to be planned well-ahead of time so that the capability can be coded into the flight control system software. Being able to analyze multiple aspects of the flight control system is the key strength of the HWIL simulation.

3.4 Iron Bird

Iron Bird simulations consist of all of the components that make up an aircraft except the skin. The term "Iron Bird" is used since most of the aircraft's mechanical/electrical components are mounted against a rigid frame sometimes made of steel, and they are arranged just as if they were in the actual aircraft. The intent of an iron bird simulator is to verify and validate that all of the mechanical/electrical components will function together as an integrated system. Often a high-fidelity HWIL manned simulator is connected to the iron bird. Possibly the only models used in the iron bird are the aerodynamics and the engines. However, in the case of the Boeing 777 aircraft development, the actual aircraft power generators from the engines were connected to the iron bird simulator so that the actual power loads and power quality could be factored into the complete simulation.

The iron bird simulator is a valuable tool for the aircraft design team, however, it has limited utility for flight dynamics testing.

3.4.1 Intended Use

In terms of flight dynamics testing, the iron bird simulator is the tool used to test for Limit Cycle Oscillations (LCO). LCOs result when the gains from the flight control system are too high and thus driving the control surfaces at their maximum rate limit. This makes it easy for the pilot to get out of phase with the aircraft's response thus producing a potentially dangerous Pilot Induced Oscillation (PIO). Flight control law designers do extensive analysis to optimize the system gains to prevent LCOs from occurring. However, not until the real hydraulics are coupled with the actuators moving aircraft control surfaces can the designers test for LCOs. Up till this point, only models of the actuators were used in the simulations. The real actuators could induce additional time delay that could drive the closed-loop flight control system to become unstable.

LCO tests are done on an iron bird simulator to avoid damaging the aircraft if a destructive oscillation does occur.

Additionally, the test engineers are able to build upon the results of the FMET tests and induce artificial failures into the system. Pilots often fly the iron bird to determine if they are able to get the complete system into a PIO.

The Boeing 777 development team took the iron bird simulator concept to new levels of fidelity. This was a key factor in being able to deliver the aircraft as "service ready". The 777 Integrated Aircraft Systems Laboratory was the major integration lab for the 777 development. The complete control system was suspended from steel beams that were the identical length of the aircraft's wing, horizontal and vertical tails. All of the hydraulic lines, electrical systems, and control cables were connected to the actuators which moved the control surfaces. As mentioned earlier, the actual aircraft power generators were used to provide electrical power to all of the systems. The power loads expected by all of the systems on-board the aircraft were simulated and connected to the power generators. A flight deck simulator consisting of engineering models and actual hardware was connected to the complete iron bird simulator. As an additional feature, Boeing used the same data system that would be used during the flight tests. In this way, they could also wring out all of the bugs from the instrumentation and data system before ever flying it aboard the test aircraft.

The Boeing engineering team used this mockup for many purposes. They induced system failures to prove that the aircraft was ready for first flight. They were able to have the maintenance team come in and validate their maintenance models using this simulator. During first flight, the simulator was used to shadow the actual flight test. That is, a pilot on the ground flew the simulator on the same profile at the same time as the pilots in the aircraft. By doing this, the Boeing team was able to troubleshoot any problems that might occur during the tests.

All total, the 777 program did 4047 hours of ground testing compared to 667 hours of ground testing on the 767. This proved itself out in flight test in that the 777 was able to sustain a higher initial flight test rate than on the 767 program. For example, during the initial flight testing, the 777 averaged 75hours/month versus 15hours/month on the 767. The team found more problems on the ground, which resulted in a higher flight test sortie rate.

3.4.2 Resources Required

To build an iron bird simulator requires an up-front commitment on the part of the design team. Laboratory space must be made available to handle the massive structure required. Additional flight components, such as hydraulic lines, actuators, etc, must be manufactured and installed in the iron bird lab. From the very beginning, Boeing built all of their Line Replaceable Unit models that were used in the engineering simulator, to the exact Interface Control Document requirements. In this way, the models could be swapped out for hardware components in their Systems Integration Lab. The final integrated aircraft simulation was developed over a period of time. Actual hardware was added as it became available.

Because of the extensive investment, iron bird simulators tend to remain for the life of the aircraft. Upgrades to airplane's hydromechanical systems, electrical or control systems, can then be conducted in the simulator and tests such as LCO, rerun to verify the aircraft's characteristics. Most test centers will not have an iron bird simulator because of the expense, and so the whole test team must make use of the developing contractors facilities.

3.5 In-Flight

The last type of simulation used for flight dynamics flight testing is in-flight simulation. Like the iron-bird, this is expensive but the payoffs can be great. In the discussion up to this point, all of the simulations have been ground based and may not have a motion simulator. Even with a full motion simulator the motion cues cannot be full scale and often suffer from time delays and other problems. In-flight simulation is the only method that allows the pilot to actually fly a simulated version of the aircraft. Flying simulators have been used to represent fighter, cargo and passenger aircraft. The type of aircraft that can be simulated by a flying simulator really depends on the simulator platform. A fighter-type aircraft is best used to simulate fighters while a transport type aircraft can represent the remaining types of aircraft.

In avionics test, flying simulators are often used to conduct tests on such components as the radar and the navigation systems. Some of the flying simulators that are used to evaluate an aircraft's flying qualities can also be used to evaluate the aircraft's avionics systems. This discussion will focus on the flying qualities testing.

In-flight simulation introduces the pilot's sensory perceptions into the task. This often results in driving up the pilot's gain and can highlight undesirable flying qualities such as PIO tendencies. The major drawback to in-flight simulation is that it does not use the actual flight control computers and the aircraft aerodynamics are still represented by a model. These deficiencies have been worked out over the years and can be accounted for in the simulation.

The Institute for Fluid Mechanics (DLR) in Braunschweig, Germany operates the Advanced Technologies Testing Aircraft System (ATTAS). The ATTAS is DLR's primary flight test vehicle to demonstrate and validate various technologies such as flight control, guidance, navigation, man-machine interactions (Reference 15). The ATTAS uses a twin-turbofan, short haul passenger aircraft VFW 614 equipped with a fly-by-wire (FBW)/fly-by-light digital flight control system (DFCS). As an in-flight simulator, the ATTAS is primarily used to represent transport type of aircraft.

In the United States, the Air Force Research Laboratory operates the Variable In-flight Stability Aircraft (VISTA). A two-seat F-16 has been modified to perform in-flight simulation for fighter type of aircraft. The front seat is used for the evaluation pilot while the safety pilot uses the back seat. Both of the above mentioned aircraft have extensive instrumentation and data capabilities to insure that required information is captured during the tests.

3.5.1 Intended Use

The best use of in-flight simulation is for well-defined, closed loop tasks. These tasks including approach and landing tasks, and precise tracking such as formation flying or refined air-to-air tracking. The flying simulator works the best when the flight control inputs are relatively small without major changes in the aircraft's rate or position. Because the test's aircraft's control laws as well as its aerodynamic characteristics must be programmed into the flying simulator's computer, large changes of AOA, pitch angle, airspeed, etc, are not practical.

Usually the lack of motion cues and the fidelity of the OTW visual scene in a ground-based simulator make it hard for the test pilot to evaluate the handling qualities during precise maneuvering. Further, the pilot has the tendency to back out of the loop if a problem happens and is not forced to drive up the gain of his input. The pilot reacting to an aircraft motion often causes PIOs but the flight control system is unable to keep up with the pilot's inputs. Thus, the tasks used in flying simulations must be setup to drive up the pilot's gains. This means that for approach and landing tasks, the pilot must be told precisely where he should touch down on the runway; or for formation flying, the evaluation pilot must be told where to precisely position himself in regards to the lead aircraft.

It is the responsibility of the safety pilot to insure that no unsafe conditions are going to occur. If the safety pilot senses a problem then the system can be rapidly converted back to the baseline aircraft configuration.

A challenge with in-flight simulation is to make the baseline aircraft behave like the test aircraft. Typically, data from MITL simulations is used to validate the flying simulator. To make the simulator fly like the real aircraft is not a simple effort. Several flights may be required to insure that the right combinations of aerodynamics and flight control will produce a response identical to one in a MITL simulation. What is important to remember is that the pilot must be actively engaged in-the-loop in order to evaluate the pilot's affect on the aircraft's flying qualities. Because the pilot is engaged, what seemed like acceptable flying qualities in the ground simulator may become in the air. Before flying tasks in a flying simulator, those tasks should be accomplished in the ground-based simulator. The same rating scale should be used for both types of simulations. For flying qualities evaluations, the best rating scale is the Cooper-Harper scale. After each task is completed the pilot must give a Cooper Harper rating. If there are differences between the two types of simulations, some explanation will be required.

The use of in-flight simulation is important in the aircraft development. If the pilot is unable to land the aircraft due to a problem such a PIO tendencies, it is desirable to find those anomalies before the first test flight. Uses of in-flight simulation are very specific, but the validity often justifies the cost.

3.5.2 Resources Required

Because of the expense in developing and maintaining an in-flight simulation capability, these systems are often national test assets. The developing contractor and the test team can rent the capability in order to do their evaluation. Aircraft like the ATTAS and the VISTA/F-16 are test tools that anyone can use. But to make the most of these expensive tools, the test team must do their homework up-front and properly define the closed-loop tasks and be prepared to have the data available to validate the flying simulation as well as to compare the final results. A lot can be learned by using in-flight simulation, but care must be taken to understand its purpose and limitations.

Use	Analytic	Engineering	HWIL	Iron-Bird	In-Flight
Planning	X	X			
Maneuver Definition	X	X			X
Anomaly Investigation		X	X		X
Test Scenario Dev		X			X
V&V of Software			X		
Failure Modes Testing			X		
Training		X	X		
Limit Cycle				X	

Figure 3.1

4 SIMULATION DEVELOPMENT CONSIDERATIONS

This chapter covers the various factors, which must be considered when building a simulation to support flight testing. Significant forethought is required in order to insure that there is time and money available to build and use the simulation. Some of the considerations that will be addressed in this chapter are: requirements definition, modeling, the cockpit, the OTW visual scene, data display and analysis, and V&V.

4.1 Requirements Definition

Knowing what you want to do with the simulation is the single most important factor in building a flight test simulator. Determining flight test simulation requirements early on in the development of the aircraft will greatly facilitate the building and validation of the simulation. Gaining early consensus from the whole team (contractor and government) that a flight test simulator is necessary will ultimately save money.

Once it has been determined that a simulator is required, the next decision is to determine the type of simulation required to support flight testing. Figure 3.1 lists of appropriate uses of M&S to support flight testing versus the type of simulation required. The use will determine the type of simulation to be built. In-depth discussion of each type of simulation is contained in chapter 3. Along with the type of simulation, the scope of the flight test simulator must be determined. That is, will the simulator cover the complete aircraft envelope or just a critical portion of it such as the high AOA region. The greater the scope of the simulation, the more extensive the aerodynamic data and flight control system models that are required. The scope of the simulation will determine the amount of computer hardware that is necessary to host the simulation. Properly scoping out the simulation will minimize the expense associated with the construction of a flight test simulator. Early on in the development it is easy to add scope, however, once the simulation is constructed it can be very difficult and expensive to go back and add capability to the simulation. For example, if the simulation was sized to just handle the high AOA regime, it may not be possible without significant changes to add in the rest of the flight envelope. Additionally, properly determining the simulation requirements will determine the amount of validation that needs to occur. If flight test data is required to validate the simulation, this needs to be known early on in the test planning so that it can be accounted for. Once again, it may be too expensive later on in the program to collect additional flight test data.

A critical decision that must be made early on is where to locate the simulator. Typically the development contractor will have at least a MITL simulator connected to a HWIL simulator. They may even go as far as having an iron bird. These simulators are often being utilized full-time during the development phase to assist in the design process and to insure that the design will meet the aircraft requirements. The flight test team can make excellent use of these contractor facilities to help define the test program and to work with the test pilots to define the type of test maneuver. However, if the aircraft is to be tested at a separate location may not be enough time to travel to the contractor's facility to support the rapid pace of a flight test program. In that case, a separate simulation must be developed at the flight test location.

Once it is determined that a dedicated flight test simulator will be built, then the next decision is the fidelity of the cockpit that is required. Once again for development purposes, the contractor will probably have a very high fidelity cockpit with actual aircraft components and hardware. As discussed in the previous chapter, this may not be required to support flight testing. It goes back to what the flight test simulation will be used for. Obviously a high fidelity cockpit will cost more money, so scoping out the proper requirements is essential. Corresponding to the cockpit fidelity is the OTW visual scene fidelity. The simulation requirements may dictate a low to medium fidelity cockpit but a high fidelity OTW visual scene. The fidelity of the visual scene depends on the tasks and the use of the flight test simulation. Reaching an early decision on the fidelity of both the cockpit and the visual scene is essential to insure that the simulation will be ready when needed by the flight test team. Another key point to remember about constructing a dedicated flight test simulation is the availability of actual aircraft flight hardware. Because the simulation will be used for flight dynamics evaluations, it is desirable that the actual aircraft stick, throttle and rudder pedals be used. If this simulation is not planned for early on, there may not be any flight hardware available for the cockpit.

If a separate flight test simulation is required, the models used in the simulation should be the same as those used by the contractor in order to avoid duplication of work and to take advantage of the model validation. However, there are instances when the flight test organization may need to construct the dedicated simulation without any inputs from the contractor. This can happen if the government test organization is required to conduct a wholly independent evaluation of the aircraft. If that is the case then the simulation engineer must specify the data format required for the aerodynamic data and the required documentation necessary to build the simulation. Even though the simulation will be independent from the developing contractor, the government engineering team will still be dependent upon the contractor to educate them on how the aircraft was designed and how the flight controls were implemented on the aircraft, as well as other needed information. There needs to be an open and continuous exchange of information between the contractor and the government if an independent flight test simulation is to be successfully constructed and used. Agreements must be established to insure the free flow of data and documentation from the contractor to the government.

Whether or not there is an independent simulation, all flight test simulations need to identify the type of data the engineers must collect from the simulation and the formats required. If simulation data is to be used in real-time during the flight test mission, then interfaces between the test control room and the simulation will be required. If simulation data is required to support the post-test analysis, then the analysis tools must be identified and the simulation data properly formatted so that it can be input into the analysis tool. Once again, it may be very difficult to modify a simulation to obtain the right data or to modify the formats. Where possible, the simulation engineer should strive to make the simulation data displays and the data formats match those being used by the flight test team. This requires a close working relationship between the test team and the simulation engineer.

Understanding the requirements for a flight test simulation is essential. There can sometimes be great reluctance to build a flight test simulator since it means additional cost to the program. However, the test team needs to be persistent to insure that the proper tools get built. Experience has shown that a flight test simulator improves the efficiency and safety of a flight test program. Saving one test aircraft from an accident easily justifies the cost of the flight test simulation.

4.2 Modeling

This section will discuss the various aspects of building models for a flight test simulation application. This is by no means an exhaustive exploration of model construction, which is almost a science in and of itself. The intent is to highlight some of the issues that the flight test engineer needs to be aware of so as to understand the strengths and weaknesses of a simulation. While simulation engineers are the experts who can translate the test engineer's requirements into models. Still, the test engineer must know where tradeoffs or assumptions have been made. This is essential if the test engineer is to properly evaluate the simulation results as compared to actual flight test results.

4.2.1 Flight Control System

This section provides a brief overview of how various flight control components are implemented in a digital simulation computer. There are several schemas for implementing these components in a digital format. The one presented here relies on the z-transformation. If the model is already trying to represent a digital flight control system, then the schema used to implement the control laws in the digital computer should be used in the simulation. This requires the test engineer and the simulation engineer to have a very good understanding of the control system and its implementation.

A digital computer works at a fixed sample time of T seconds. That is, in each computer there is a clock, which supplies a signal every *T* seconds. *T* is defined as the sample rate. The smaller the sample rate, the faster the computer is able to do calculations.

In an airplane, most data is being sensed by analog instruments like a pressure probe. This means that data is then converted to a digital signal through an Analog to Digital (A/D) converter. The rate at which the digital computer samples the data and then makes calculations on that data is called the sample rate, or often referred to as the frame time. One frame is the time it takes to sample the digital signal, do the calculations, and output the result. The smaller the frame time, the closer the digital computer comes to representing an analog computer.

In order to analyze a digital computer a way must be found to model it. A z-Transform is similar to a Laplace-transform except it is in the z plane. The z plane allows for discrete modeling of sampled-data systems. A z-transformation is a discrete transfer function of the ratio of output samples to input samples. References 16 and 17 contain a detailed description of the z-transformation derivation and the z-plane transfer functions.

Of particular interest to this for this report is the implementation of electronic filters especially digital filters. A filter is designed to pass through certain signal frequencies while rejecting the other signal frequencies. In an analog system, filter implementation is easy because the signal is continuous. In a digital system the continuous filter must be mathematically transformed to accept discrete signals. Therefore the difficulty lies in determining a z-plane transfer function that best emulates an analog filter.

Appendix A presents a detailed derivation for determining the z-plane transform of a filter. While there are certainly other mathematical representations for flight control system components. Some functions in the control system do not need converted from the s-plane to the z-plane. The other functions used in a simulation computer program can be coded directly without any mathematical manipulations. These derivations are meant to educate the test engineer as to the complexity involved in creating a realistic flight control simulation. Further it should illustrate that proper validation of the simulation will require an in-depth understanding of how the various control system components are implemented both in the flight control computer and in the digital simulation.

4.2.2 Aerodynamics

Aerodynamic modeling is different from flight control system modeling. It is more dependent upon lookups, interpolation and extrapolation of data obtained from wind tunnel tests. Once again knowing the scope of the required simulation is critical to obtaining the proper aerodynamic data. Fairly extensive aerodynamic models will often exceed 100,000 points. One technique to access this data is to put the data into tables. These tables can be a function of airspeed, altitude, Mach Number, depending upon how the simulation engineer designs the aerodynamic model.

This kind of massive aerodynamic database requires significant computer resources. With the advent of cheap supercomputers, hosting a large aerodynamic database used to be very difficult. However, if resources are limited or if speed is a critical factor, some simplifying assumptions will be required. A technique to do this is to look for regions in the aerodynamic data that are linear and then just pick the starting and end points instead of all of the data in between. For example, pitching moment (C_m) is a function of AOA (α). Suppose wind tunnel data has been collected at AOAs ranging from 1 to 30 degrees in 1 degree increments. Further suppose that in the region between 10 and 20 degrees AOA, there is no change in C_m. The C_m versus α lookup table could be shrunk down from 30 data points to 20 data points. This would save memory and possibly save time as well. A piece of software code would have to be written to account for the data between 10 and 20 degrees AOA, but that requires less execution time.

Likewise, if the simulation covers regions that have no aerodynamic data, then an extrapolation routine will have to be written to cover those regions. A word of caution, extrapolations beyond known wind tunnel data should only be undertaken after a lot of consideration. The same can be said for omitting aerodynamic data or linearizing data. The flight test engineer must have a complete understanding of all of the assumptions or efficiencies that were made in the construction of the aerodynamic model. Hopefully, the aerodynamic model that is used in the flight test simulator is the same one used by the contractor. This will greatly ease the V&V task.

4.2.3 Environment

Environmental modeling refers to the equations of motion (EOM) and the atmospheric models. These models are very standard and can be easily created. However, there are some decisions that must be made by the simulation and flight test engineers.

For atmospheric models, the engineers must decide if the models will reflect standard or non-standard days. A constant temperature bias, ΔT, can be added to the standard day temperature profile to obtain a hot or cold day temperature profile. Typically the atmospheric model will only cover altitudes up to 100,000 feet. Altitudes greater than that will require different calculations and assumptions (for example, gravity will have to be considered). Besides calculating temperature and pressures, the atmospheric model will have to calculate variables such as Mach Number, impact pressure, calibrated airspeed, etc. The simulation engineer should be able to locate the source of the equations used in the atmospheric model.

The equations of motion (EOM) are again easily identified but some understanding of the assumptions is important. Most full fidelity simulations will have six degrees-of-freedom (DOF): three rotational DOFs and three translational DOFs. However, some simulations only work in five DOFs. The engineer must know the degrees-of-freedom before using the simulation. The engineer also needs to know whether or not the EOMs have been corrected for variations in center-of-gravity, and whether or not thrust induced moments and landing gear moments are added to the aerodynamic moments to get the total moments which are acting on the aircraft. Since mathematical integration is required to obtain accelerations, the engineers need to understand the numerical methods employed. Also, the engineer needs to understand if the EOMs take into account asymmetric loadings. Certain simplifying assumptions regarding the aircraft's inertia is symmetry is assumed. These are the easily overlooked problems that can make validation of the model and simulation very difficult. When differences do exist between the simulation data and in-flight data it may be caused by simplifying assumption that is no longer valid.

4.3 Cockpit

The issue of cockpits and the required fidelity was touched on in Chapter 3. From a pilot's perspective, the cockpit is the most important feature of the whole simulation. A poorly configured cockpit can result in "negative" learning and effect the results coming from a simulation. It would be easy to say that all simulation cockpits must be identical to the aircraft's cockpit, however, that is not always the case. Availability of cockpit components, cost, and time to build a cockpit are all considerations when deciding on a cockpit design. Three key areas to be considered in cockpit development are fidelity, displays, and force feel system. These are discussed in the sections below.

4.3.1 Fidelity

The fidelity required in a cockpit is determined by the desired use of the simulation. The various uses of a simulation are covered in Section 3. It is always better to have a high fidelity cockpit compared to a low fidelity cockpit. A high fidelity cockpit is one that would duplicate the aircraft's cockpit. The pilot would not be able to tell whether he is sitting in the airplane or in a simulator cockpit. A low fidelity cockpit may only duplicate a few of the actual cockpit details. Some cockpits used for engineering purposes may only have a generic stick, throttle and rudder pedals, and these may not even match those in the airplane. Typically, for flight test purposes, the cockpit falls somewhere in the middle between the two fidelity extremes. For flight dynamics flight testing, there are some critical components of the cockpit which must match the actual aircraft. Some of these are: the actual stick and throttle; exact placement in the cockpit of key gauges like airspeed, altitude, mach number; some form of head-up-display (HUD) that duplicates the aircraft's displays; key switches such as engine and spin chute. Many of the other cockpit functions can be non-working or just replicas of the actual cockpit function.

For open loop simulation tests, such as pitch doublets or aircraft roll maneuvers, minimum cockpit fidelity is sufficient. However, even for these maneuvers, stick force must be properly modeled. It is the aircraft's response to pilot inputs that is critical, and not the pilot's reaction or his feedback. For closed-loop maneuvers such as tracking or high AOA recovery, a higher level of cockpit fidelity is necessary since the pilot's response is essential in evaluating the aircraft's flight characteristics.

Along with the physical layout and characteristics of the cockpit, the models the level of model fidelity should match the cockpit. For example, developing a recovery procedure for an engine stall requires a complete set of engine switches in the cockpit. However, if the software only models simple engine thrust using a lookup table, then there is a crucial mismatch between the cockpit and the models. Thus, the simulation engineer needs to thoroughly plan for not only cockpit hardware development, but also cockpit software development.

4.3.2 Displays

The matching of cockpit hardware and software is very important, and very difficult when dealing with the cockpit displays. All modern aircraft have glass cockpits. Very often in aircraft development programs the cost of using the actual avionics in a flight test simulator is prohibitive. Therefore, the simulation engineer must often simulate the displays. These displays often have critical flight information such as airspeed, altitude, and other mandatory information. The transition from instruments to glass cockpit displays has complicated the simulation engineer's task to build a representative cockpit.

The simulation engineer must work closely with the test team to understand the cockpit display requirements. For example, if the actual displays are in color, is it required to have color displays in the cockpit? What functions must be duplicated by the simulated cockpit displays? Should all displays be fully functional, or can some just be false screens?

Typically, flight control system status information is presented on the cockpit's displays. If flight controls tests are to be conducted in the simulator, the pilot or engineer must be able to access the flight control system information from the displays. This may require extensive software development both in the displays and in the flight control system models being used. This kind of complexity also increases the V&V complexity. Eventually, there comes a point where the amount of effort required to design, build, and conduct V&V on the displays warrants the inclusion of the actual aircraft hardware. However, the use of real hardware in a flight test simulator drives up the cost of the simulation and may limit its availability and utility in supporting the test program.

Fortunately, there are numerous commercial hardware and software tools available that will allow the software engineer to model the real cockpit displays. The test engineer needs to remember that the simulation engineer is not trying to duplicate the complete operations of the avionics system, rather the engineer is attempting to provide the critical functions necessary to conduct the appropriate simulation tests. Thus, determining the use of the simulation early on in the program will save time and money over the long run.

4.3.3 Force-Feel Systems

An often overlooked component in developing a simulator cockpit is the force-feel system. The aircraft's cockpit controls, such as the stick, will be tuned to have a certain sensitivity or a certain stick resistance. Aircraft that have fixed side-sticks such as the F-16 do not require a force feel system in their simulator cockpits. These sticks measure pounds of input (pull or push) and convert it to an electric signal that is sent to the flight controls. However, the vast majority of aircraft have center sticks that travel a certain distance when pushed or pulled.

It is absolutely essential that simulator cockpit have the same feel as the real aircraft. This is true whether open or closed-loop maneuvers are being performed. If the stick feel is off, the pilot input and corresponding aircraft response will not match the actual aircraft.

4.4 Visual Scene

The Out-the-Window (OTW) visual scene is an extremely important element that determines the utility and usefulness of a simulation. The visual scene consists of two critical components: the image generator (IG) and the Visual Display System (VDS). The IG creates the visual scene that is then displayed to the pilot with the VDS. Image generation is almost exclusively accomplished using high-powered graphics computers while there are a variety of technical solutions that can be applied to the VDS.

The importance of an appropriate visual scene cannot be understated. As stated in Reference 17, "Successful pilot training (and research investigations that use pilot evaluations) is only possible if the pilots accept the simulator, for what it can and cannot do. A visual display system adds greatly to this acceptance. The illusion of flight is only successful if the pilot can relate to the flight situation and divorce himself from the idea of sitting in a box, performing a stylized, though difficult, task." The challenge faced by the simulation and test engineers is to strike a balance between complex, high-fidelity visual scenes and simple, cartoon-like visual scenes. Tailoring the visual scene to meet the required simulation task requires some forethought.

In the early days of manned simulators, and into the 1970's, pilots routinely performed open-loop flight test tasks without any visual scene. These tests usually consisted of stick or rudder pedal wraps, or airplane rolls. The pilot would simply use the cockpit gages to establish the appropriate flight condition. The goal from these tasks was to provide data to the engineers to prepare for flight tests. As flight tests became more sophisticated and began to employ techniques such as HQDT, the pilots demanded more and more complex visual scenes.

In many fighter-type simulators, the visual scene is the only external cue that the pilot may have. Again as stated in Reference 17: "The pilot may not need to use the same visual inputs or cues in the simulator as he does in the aircraft, but a basic assumption would be that he needs to be able to control the simulator with the same degree of precision and with the same control strategy as he controls the aircraft, using visual cues as the only source of information regarding the velocity and orientation of the aircraft. This assumption would seem to be reasonable for both training and research simulators. The analysis of simple control tasks would not only be useful in itself but would provide insight into how the more complex visual tasks could be analyzed." This statement supports the contention that if the simulator is to be used to support closed-loop handling qualities testing, that the visual system must provide a level of fidelity appropriate enough to compare the simulator results to the flight test results.

4.4.1 Image Generator

Image generation (IG) technology has progressed very rapidly in the last few years. While this technology used to be the proprietary domain of specialty companies such as Evans and Sutherland (E&S), companies such as Silicon Graphics Inc. (SGI) have developed a whole line of very powerful non-proprietary IG machines. The computational power is just part of the IG requirement. Software is necessary to take digital data and turn it into the visual scene renderings. The complexity of the scene is usually given in terms of number of polygons. The software used to translate the data has also become commercially available. The combination of off-the-shelf hardware and software has allowed the simulation engineer to create complex OTW visual scenes at a fraction of the cost of the previously associated with visual scenes. It also allows the engineer to modify the visual scene and tailor it to meet a specific test requirement.

The capability of the IG determines the quality and appearance of the OTW visual scene. Since all of this processing must be done in real-time, there are a number of factors that contribute to the quality of the scene being displayed. Reference 18 discusses 5 factors that influence the IG capability. These are: scene content, image quality, image update rate, latency, and resolution. If the reader is interested in understand these factors in more detail, this reference provides and in-depth discussion of these factors.

The IG must be capable of processing the visual scene data in real-time at a rate of at least 30 times per second (30 Hz) and preferably 60 Hz. For a complex test task such as HQDT, the total time delay as seen by the pilot should be 0.1 sec or less. This is measured from the time the pilot provides and input until the OTW scene moves. Reference 17 provides a comprehensive explanation on the importance of minimizing the time delay and of various techniques to measure visual scene time delays.

The image generator must typically render three types of objects: the terrain, cultural objects (manmade or natural), and animated objects (Reference 18). The terrain model is typically generated from Digital Terrain Elevation Data (DTED). This data contains varying levels of resolution. The finer the resolution of the terrain data (e.g. 100 foot grids), the more computational power required to generate the terrain model. The resolution of terrain required depends on the task trying to be accomplished with the simulator. In reference 18, sufficiently detailed terrain models could not be created by the IG, therefore low level, high speed mission training was not entirely possible with the current simulator technology. However, for a slow moving aircraft such as a helicopter, very detailed terrain models can be created since the helicopter does not cover as much terrain as a fighter airplane.

The objects that are placed on to the terrain also contribute to the realism of the OTW scene. Simple cartoon objects such as trees, houses, or roads, tend to subtract from the believability of the simulation. Great care should be taken when deciding what objects to place in the visual scene. For the landing task the rendering of the runway and the area around it (such as buildings that provide height cues to the pilot) should be of the highest fidelity. Skid marks, strips, runway lights and signs are just examples of the objects that will make the scene more realistic to the pilot.

A technique to achieve the highest level of fidelity is through Photo-texturing. This process takes an actual digital photograph of the area such as a runway, and overlays it on top of the DTED terrain model. The drawback of using this technique is that it requires a large amount of storage and real-time processing capability. Photo-texturing is usually done for small areas such as an airbase. Objects created by polygons are still required in order to provide measurable heights for simulated systems such as the radar.

The animated objects is another aspect of the visual scene. In these applications, animated objects are typically used as targets to be tracked by the pilot. The need for the correct level of detail of these animated objects depends on the task required. If the pilot is going to use the simulator to determine closed-loop handling qualities during refueling, then the level of detail required for the tanker would be very high. This would pertain to all aspects of the tanker including refueling lights. Additionally, air-to-air tracking tasks also require high levels of detail. Being able to determine aspect angle and direction of flight is critical for the pilot to perform the appropriate closed-loop test maneuver.

The behavior of these animated objects must follow the laws of physics. However, pre-programmed targets have limited maneuverability such as a constant "g" turn or an s-weave pattern. Pilots quickly adapt to the target motion, and as a result, their inputs may not represent their real world inputs. Of course, in flight testing, real target aircraft may fly pre-defined paths such as constant "g" turn. These pre-defined maneuvers allow a fairly good comparison between the simulator tracking results and the actual test results. A method to insure even better correlation is to record the movement of the target aircraft and then play that back into the simulation and display it to the pilot. Once again, the visual acuity of the generated scene and the level of fidelity will determine the simulator pilot's ability to properly track the target aircraft. If conducting such tests in a simulator is desirable in the flight test program then sufficient time and resources need to be allocated to visual scene development.

If pre-programmed simulation targets is not sufficient to meet the requirements, then the next best option is to fly one simulator against another simulator. That is, link together two MITL simulators. One simulator would act as the target and the other would be the test aircraft. From a test perspective the significant drawback to this approach is the lack of results repeatability and an inability to correlate the data with actual flight testing. However, the development test team could use this simulator technique to be a confidence builder to insure that the test aircraft can be maneuvered with abandon as would occur in an actual combat situation.

One of the concerns with linking two simulators together is the latency between the two simulators. The IG needs to obtain current aircraft position from both of the simulators and then it has to create the correct image and then that image must be displayed on the OTW scene. All of this must be done within the time parameters previously discussed. These rigid timing requirements still pose a technical challenge. Because of the costs, technical challenges, and the limited usefulness of linking two simulators together to support development testing, this option is not usually developed or used to support flight testing.

4.4.2 Visual Display System

The VDS projects the image received from the IG. There are several factors that influence the capabilities of the VDS. First, and foremost, is the test requirement. As stated earlier, the visual scene needs to provide sufficient visual cues so that the pilot can perform the task just as if he were flying. For example, up and away flying or test points that just require open loop pilot inputs, only require a field-of-view (FOV) of 48 degrees horizontally by 36 degrees vertical (Reference 20). This provides sufficient visual cues for the pilot to fly the aircraft straight-ahead. A high gain landing task requires a wider horizontal FOV so that the pilot's peripheral vision can be used to judge height off of the ground. Simple HQDT tracking of a constant "g" target requires a FOV wide enough for the pilot to perceive an offset that must be corrected. Likewise, an aerial refueling task requires a large vertical FOV and the standard horizontal FOV. Whereas, high AOA maneuvers like spins or unconstrained target maneuvering requires a 360 degree VDS. Determination of the required FOV is essential to designing the proper VDS.

The next factor that influences VDS capabilities is a combination of two interdependencies: the output capability of the IG and the display capability of the projectors. The number of pixels that can be produced by the IG will determine the visual acuity and resolution of the OTW visual scene. The number of pixels that the IG can produce is important. Current state-of-the-art IG systems can produce up to 2 million pixels for display at a 60 hertz rate. The display device that receives this input must be capable of displaying all of these pixels coming from the IG. If the projectors cannot handle the level of resolution being generated by the IG, then there is a mismatch in the visual scene design. Spending a lot of money on a state-of-the-art IG requires a corresponding investment in high-end projectors. Fortunately, projector technology is moving ahead at a pace corresponding to the pace of IG progress. The screens on which the projectors project their images must also be considered when designing the visual scene. The complexity of designing and implementing a high-end visual scene usually requires specialized expertise. The average simulation can work with the test team to specify the visual scene requirements, but experts are typically required to create and maintain these complex visual systems.

4.4.3 State-of-the-art Example

All of these factors must come together and the simulation engineering and the test team must decide on a design of the simulator visual scene. Prior to the mid-1990's, a straight-ahead visual system was the most common for flight test simulators. The VDS used was either television monitor or some form of projector. Costs were usually the driver that prevented more expansive OTW visual scenes. This limited visual scene restricted the maneuvers that could be accomplished in a simulator. The ideal was to have a 360-degree visual system, however this was not practical. Only the large aerospace companies and the training commands could afford a 360-degree visual system. To obtain the OTW visual scene, the images were projected on a large white dome. These domes were very expensive to operate and maintain. They also suffered from reduced brightness and visual acuity suffered because of the large dome size and the projector technology.

The AFFTC at Edwards AFB had a requirement to provide a 360-degree visual system to support some unique testing. The simulation group at the AFFTC leveraged on some new display techniques developed by the Air Force Research Lab at Mesa, Arizona. Using the lab technologies the simulation group developed a low-cost 360-degree OTW visual scene without the need for a dome. Figure 4-1 shows the basic layout of this capability. This system is called the Test and Evaluation Modeling and Simulation (TEMS) mini-dome. To produce the images the AFFTC relied on commercially available IG systems and software. Figure 4-2, 4-3 and 4-4 are samples of the quality of the image that is produced by the IG. Note that in Figure 4-3, the IG has the capability of generating a cloud deck.

The TEMS mini-dome is comprised of 8 individual flat screens that provide a horizontal FOV of 360 degrees and a vertical FOV of 215 degrees. This FOV enables the pilot to perform all test-related tasks including unconstrained tracking and maneuvering. The OTW visual scene definition supports closed-loop handling qualities tests for the approach and landing task. The average distance from the pilot's eye point to the screen is 30 inches. This allows for very bright screen displays. Being so close also provides a sense of immersion, like the real world, for the pilot. At low flight altitudes, the close proximity of the side screens provides a sense of speed for the pilot's peripheral cues.

The database uses Level-1 DTED data and covers an area of more than 200,000 square miles in the southwestern United States. This data is translated into an IG database containing 5.4 million polygons. Of these, 4.4 million polygons represent the terrain and 1.0 million polygons represent 3-dimensional features. However the database can accommodate a 50-50 mix between terrain and 3-dimensional features. Thus, the database can hold another 3.4 million polygons of 3-dimensional objects. The capability to include photo-texturing is also built into the database. The IG is capable of producing an image of up to 2 million pixels in a 1600x1200 pixel display.

The VDS projectors are also commercially available equipment. These multisynch projectors can support color image resolutions up to 2500x2000 pixels. However, the video bandwidth of 135 Megahertz causes some image degradation at resolutions higher than 1280x1024 pixels. The projectors also provide a minimum of 200 lumens (over 1000 lumens peak white), and contrast ratios in excess of 100:1

Because the whole visual scene system uses commercial equipment and technology, the cost of the TEMS mini-dome system is an order of magnitude less than that of a regular domed simulator. The system also provides improved capabilities over the traditional domed simulators. Additionally, the TEMS mini-dome does not require any special environmental conditions and can be set up in normal room without any special power or unique facility modifications.

However, all of this technology is not important if the simulator cannot meet the test requirements. The TEMS mini-dome has been successfully supporting flight tests and the feedback from the pilot's has been overwhelmingly supportive. The TEMS mini-dome opens a new era of flight test simulator capabilities.

4.4.4 Helmet Mounted Displays

For the past two decades there has been research in developing Helmet Mounted Displays (HMDs) that can be used in lieu of the typical visual scene systems described above. The pilot wears the HMD and the visual scene is projected directly in front of the pilot's eye. The HMD uses images generated by an IG. The FOV, resolution, brightness and other factors vary between HMD types.

The concept behind the HMD is that it eliminates the cumbersome infrastructure associated with a traditional VDS. This allows for additional flexibility such as accommodating motion-based platforms, dual seat fighter operations, or even side-by-side operations. Use of an HMD reduces the space required to house a simulator since there is no VDS infrastructure. With the image so close to the pilot's eye, the pilot is immersed in the visual scene and not distracted by typical limited FOV visual systems.

However, the HMD does have some drawbacks. It requires that the pilot wear a helmet heavier than normal that must be custom fitted for each pilot. This helmet also reduces normal visibility in the cockpit. The fiber optic connections to the HMD also impede the pilot's head movement that may impact his ability to conduct certain tasks such as air-to-air tracking. HMD is also restricted in Field of View.

While HMD technology has improved dramatically over the years, there are still too many drawbacks to recommend it for the use in flight test simulators. As stated earlier, the goal of a visual system is to try and duplicate the real environment as close as possible so comparisons can be made between the simulator and real tests. The HMD creates an artificial environment that may reduce the utility of the simulator to support flight testing.

4.5 Data Display and Analysis

The data to be collected, how it will be displayed, and data formats are critical questions that should be answered early in simulator design process. It is imperative that the data requirements be identified when the basic simulator requirements are being defined. The type of data begin gathered will influence how the models are constructed and the how the basic simulation is constructed. As stated earlier, if internal flight control system parameters are required for data analysis, the simulation engineer must insure that the models are defined to that level of detail and that the intermediate parameters are output for display and analysis.

4.5.1 Types of Data Analysis

Deciding on the type of data analysis to be conducted is the first thing that must be decided in order to specify the data. There are two primary kinds of simulation analysis: real-time analysis and post-simulation analysis. The simulation user first needs to decide if they will view the data during the simulation or conduct post-simulation data analysis. Of course for non-real time simulations, the data will be analyzed after the simulation is completed. However, even for non-real time simulations, the user must specify the format of the data to be collected so that the data can be imported into analysis software.

4.5.1.1 Real-Time Analysis

The most prevalent type of data analysis is conducted during the simulation testing. For all simulation tests except non real-time, or analytic simulations, most of the data is collected, analyzed and reviewed while the simulation is being conducted. The data can be as simple as watching over the pilot's shoulder and asking questions, to analyzing complex plots. It all depends on the requirement.

For MITL simulations, experience has shown that the real-time display set up should correspond closely to the displays being used to monitor the actual test mission. As discussed earlier in the report, training the flight test engineering support team is as important as training the pilot. If at all possible, the same or similar data displays should be used, as well as the same control room layout. Parameter names and locations on the displays should be the same as the actual control room. This requires that the simulation engineer and the test team's engineer data engineer work together to insure that any changes made in the actual control room are reflected in the simulation

The analysis done on the data during the simulation often does not require complex data processing routines. Once again MITL or HWIL simulations are usually conducted to verify that it is safe to fly or that the control system is working properly, or that some other function will not degrade handling qualities. Real-time simulations are not often used to justify design decisions, but they may be used to support design tradeoffs if the pilot's input is required prior to making the design decision.

Regardless of what data is being examined in real-time, it is imperative that the data requirements be defined early-on so as to be available during the simulation. Also, requesting all available data may not be in best interest of the simulation. The simulation engineer must be concerned with timing and data transmission bandwidth. Depending upon the simulation's executive and overhead, it may not be practical to transmit all of the data and still keep the simulation within the real-time requirements. The test engineer should specify the data really required in order to conduct the specific test.

4.5.1.2 Post-Simulation Analysis

The principle lesson to be remembered regarding post-simulation analysis is the ability to format the data so that it can be used with the test engineer's standard data reduction and analysis routines. With the explosive growth in capability of the personal computer, many test engineers now use commercially available products to do their data analysis instead of depending upon customized data routines that reside on a central or mainframe computer. The test engineer must specify to the simulation engineer the format of the required data, and possibly even a copy of the data analysis software that the engineer will be using. This will insure that the data being produced by the simulation will be compatible.

The analysis of non real-time simulation results supports test planning, envelope clearance, or test maneuver definition. The test engineer may also use the data to support V&V of the simulation (discussed in more detail in the next section). Typically, the test engineer will build a summary plot that can be easily compared with data gathered during the actual test event. These plots present data such as maximum roll rate obtained at a particular altitude, or maximum g obtained during a series of wind-up turns. An Example is shown in Figure 4-5.

The Data in this plot is does not represent actual data, rather it is used as an illustration of the type of plot that can be used for analysis. The engineer would use this plot to predict aircraft performance and then plot the actual test data against the predicted simulation data. The engineer can also use this data to look for trends that could result in safety concerns.

A key point to remember is the quality of the input that generated the roll rate. In non real-time simulations, the input is usually perfect. However, in actual flight testing, the input is often less that perfect. The differences in input can significantly change the aircraft's response. The test engineer must factor this in when comparing the data plots.

Typically, the test engineer will carry a portfolio of data plots in the control room that contain simulator data results from all over the envelope. The tendency is to do all of the simulations prior to the start of the flight test program. However, as the test program progresses, changes may be made to the aircraft's flight control system that could impact the simulation results. As these changes occur, which are inevitable in many development test programs, the test engineer must constantly reevaluate the impact of the changes to the predicted data plots. To preclude this, the test engineer should limit the simulation runs to the upcoming test flights. This may require conducting simulations every week and plotting out the data, but that is a better method than having to redo all of the data plots after a flight control system change has been made.

The important point to remember is to have a data analysis plan developed and agreed upon at the outset of the simulation test program. This should be detailed sufficiently to help the simulation engineer design the data structures for the simulation, and for the test team to understand the type and use of the data that is collected. Like all else, adequate planing is important for the success of the simulation effort.

4.5.2 Simulation and Flight Test Integration

One of the key technical advances during the recent years has been the ability to integrate simulations during the actual test mission. There are three methods for accomplishing this. The first method is to electronically import previously conducted simulation results. The second method is to actually run the simulation in the control room while the mission is being conducted, the third method is to have a MITL simulation "shadowing" the actual flight test mission. All of these techniques have shown that the productivity of the flight tests is greatly enhanced.

4.5.2.1 Comparison with Previous Simulation Results

This method allows for the insertion of previously collected simulation data into the flight test control room. Typically, the simulation data is displayed on graphics terminals instead of the paper plots described earlier. The flight test data is then displayed on the same plot so that the test engineer can see during real-time how the actual testing tracks against the predictions.

The usefulness of this tool is that it frees the test engineer from having to reference many different paper plots, and it automates the process of extracting the flight test data and plotting it against the predictions. This allows for more rapid turnaround of test point maneuver clearance and increased accuracy of the results. Additionally, the data from flight test can be processed to take into account any necessary instrumentation corrections that must be done on the raw data.

A note of caution regarding this capability is to insure that the flight and simulation data can be accurately compared. That is, the airspeed, altitude, aircraft configuration (gross weight and center-of-gravity), as well as pilot input, are well-controlled so that the results can be properly compared.

4.5.2.2 Running Simulations in the Control Room

One of the most recent advances has been the ability to run the actual simulation in the flight test control room. The advent of powerful workstations and personal computers has permitted this innovation to migrate away from large mainframe computers, and into the control room. The models that comprise the simulations are actually hosted on computers in the control room. These models then use the actual aircraft parameters as inputs into the simulation. The results of the simulation are compared against the actual aircraft's response. This method permits a much closer comparison of data since the same flight conditions and pilot inputs are being used. The test engineer must still account for any instrumentation corrections that must be made on the flight test data, but this can be accomplished in real-time.

British Aerospace is using a technique called Flight Mechanics Reprediction (Ref 12) on the EF2000 test program. The aircraft's actual state and flight conditions are input into the model prior to the start of a maneuver and also compared against pre-defined conditions. If all of the conditions are within tolerances, the maneuver is executed. Then actual test maneuver information is fed into the model and the results are compared against the predictions. If the results fall within a proscribed tolerance band then the test pilot is given the clearance to proceed on to the next test point. All of this requires approximately two minutes after the maneuver is completed.

This type of simulation and test capability can be carried beyond flight dynamics testing and it can support loads and flutter testing as well. The key is the creation of models that can run sufficiently quickly in the test control room and the ability of the models to receive actual flight test data. Flight test data noise and dropouts must be factored in to the creation of the control room simulation and accounted for during the analysis.

Running simulations in the control room has the ability to revolutionize the flight test business. The ability to rapidly do the analysis will decrease the time required to do basic flight dynamics testing and improve the flight safety of testing. Maintaining configuration control between the control room simulations and the actual lab simulations is important to insure the all models are updated at the same time.

4.5.2.3 Simulation Shadowing

A third, but lesser used technique is to shadow the flight test with a MITL simulation. That is, a corresponding crew flies the simulator at the same time the test aircraft is actually flying. The main purpose of this is to resolve anomalies by using the MITL simulator as a trouble-shooting tool. The simulator pilot flies the same profile, including test points, at the same time the test aircraft is actually conducting the real test. If an anomaly occurs onboard the actual aircraft, the simulator pilot and engineers will try and duplicate the problem or to provide a work-around so that the test may continue. Because of the expense and complications involved, this type of simulation capability is usually reserved for use on high-risk or high visibility test flights.

4.6 Verification and Validation (V&V)

One of the key responsibilities of the test engineer is insure that V&V is properly done on the simulation. As a reminder, verification is defined as the process of determining that a model or simulation implementation accurately represents the developer's conceptual description and specification. Verification also evaluates the extent to which the model or simulation has been developed using sound and established software engineering practices. Validation is the process of determining the degree which a model or simulation is an accurate representation of the real world from the perspective of the intended uses of the model or simulation.

As seen from the above definitions, verification and validation are two separate activities. Typically verification precedes validation. Verification requires an understanding of the simulation requirements and how those requirements are translated into actual computer code. Validation requires a comparison of the simulation data against the actual test data. This is done from the perspective of the intended use of the simulation. Both of these processes require active involvement of the test engineer and the simulation engineer. V&V can be a cumbersome, time consuming process and must be adequately planned out before undertaking the effort. The program must allow sufficient time to do these tasks, or else the simulation results will be meaningless. More detail on each of these processes is covered in the sections below.

4.6.1 Verification Process

The verification process begins with the test engineer and the simulation engineer reaching an understanding on the requirements for the simulation. The simulation engineer translates those requirements into actual computer code. Verification then insures that the requirements were correctly translated into computer code. For example, reference Figure 4-6. This represents a typical summing junction that is found in control systems. To verify this module was implemented correctly in the software code, the simulation engineer would execute the code using known inputs that lead to a known output. For example, each input can have the value of '1", therefore the output would be expected to be "2". Once this is done, the simulation engineer would then verify that this module is correctly implemented. The test engineer should insure that proper verification techniques are being followed, but does not have to accomplish the actual verification. The test engineer must be able to assist the simulation engineer in understanding how a module is designed to function so that the simulation engineer can apply the proper verification techniques. This not only applies to flight control laws, but to all other models including aerodynamic data.

The verification process should be an ongoing process as the models are being built. The test engineer must insure that the simulation developer is equipped with the latest information regarding the system being modeled and any changes that might occur to the system. The simulation developer must insure that there is a robust configuration management effort over the models so that any changes are properly documented and tracked and that the correct version is used for validation and testing.

Verification is a process that any qualified software developer will follow. The test engineer cannot oversee the whole verification process but must remain cognizant of the results and any discrepancies or questions that might arise.

4.6.2 Validation Process

The validation process is much more complex and requires and active involvement on both the test and simulation engineer's part. Reference 11 provides an excellent overview of validation in regards to piloted simulation. Clearly the first step in developing a validation plan is to understand the intended use of the simulation. There is no need to conduct an extensive validation effort across the whole flight envelope if the simulation will only support high AOA testing. These kind of questions need to be addressed early on in the simulation requirements definition phase. Another consideration to decide on early is the ability to collect necessary flight test data in order to validate the simulator. If the correct parameters are not specified in the aircraft's instrumentation design, key data may not be available to validate the models and simulation.

A distinction needs to be made here between validating the models and validating the entire integrated simulation. A flight control law model is only concerned with the aircraft's control system. Validating that model is only a piece of the entire simulation. How each of the models passes data and the timing and synchronization of the models will determine if the entire simulation is validated. For example, data latency problems between the output of the control system model and the input into the aerodynamic model may cause the eventual result to not match flight test data. Yet, each of the models unto themselves were V&V'd, the complete integrated simulation must also be validated. This can be a complex task especially trying to track down discrepancies.

What happens if no flight test data is available to do the simulation validation? This is typically the case when a new aircraft is developed. A method of the flight test simulator is to use data from the developing contractor's simulator as the truth data. While this is not ideal, it does represent the best information available with a new aircraft. Obtaining contractor data can be difficult if it is not part of the development contract. Producing data to validate a flight test simulator often requires the expenditure of contractor resources and the contractor has the right to be compensated for those expended resources. It is in the best interest of all parties to have the contractor data negotiated as a deliverable as part of the development contract. This emphasizes the need for an open and continuous dialog with the contractor's simulation engineers. It is even prudent to set up periodic technical exchange meetings to insure that simulation and test engineers are exchanging ideas and working out problems as the simulation is being developed.

So how does the test engineer validate a test simulation. The tried and true method is to compare time history responses to various inputs over the range of the flight test envelope of interest. Figure 4-7 is a representative plot of a parameter taken from simulation and flight test. These parameters could be pitchrate, rollrate, acceleration, or any other dynamic function that varies over time. The flight test engineer is challenged with determining whether or not this data represents a validated simulation. Notice that at the top of the curve, there is a slight difference between the simulation results and the test results. The test engineer must first determine if this difference is significant and if so, then what causes that difference. This is where it can be a long a tedious process. First, the engineer must factor out any differences in aircraft state and input. This is where running a simulation in the control room (section 4.5.2.2) can become a valuable tool. If the engineer eliminates any difference in the aircraft state or inputs, then the engineer must look at the verification results. This is the payoff from early specification of aircraft instrumentation and simulation instrumentation parameters. The engineer should search for intermediate data points between input and response. If this a curve of pitchrate, the engineer may want to look at the outputs of various functions in the control laws such as gains, integrators or critical summing junctions to insure that the model and the actual control system track during the maneuver. Without these intermediate parameters it is virtually impossible to determine the source of differences without a lot of trial error simulation runs. The engineer will want to look at the output of the actuators and verify the surface positions between the simulator and the airplane. If all of these factors check out, then the test and simulation engineers must turn their attention towards the aerodynamics. There is no easy method to determine if the aerodynamic model does not match the aircraft's aerodynamics. There are parameter identification tools that can help sort this out, and if the engineer needs to use those tools then they must do so. A technique to investigate an aerodynamic difference is to modify some key aero parameters and rerun the data. A systematic approach could converge to an answer very quickly. Another method is to examine a series of comparisons to see if their is a trend from which the engineer may be able to make an educated guess as to where to look for the differences.

If there are no apparent, then the discrepancy should be noted and possibly turned over to the developing contractor for further investigation. The test team may choose to develop a test workaround until the discrepancy can be identified and fixed, or the testing could proceed with heightened awareness that there is an anomaly. Certainly, if subsequent data shows that the difference is increasing in an unsafe direction, then the testing should be stopped and the cause must be determined.

There are instances when these validation efforts will point to a problem with the aircraft such as an incorrect implementation of the control laws or an instrumentation problem, or some other aircraft anomaly. If there is an aircraft problem, the test engineer must do flight test regression testing and go back and redo the simulation validation process.

4.6.3 How Much Validation is Enough?

Deciding on the extent of the validation program is one of the critical decisions the test engineering team must make. One of the criteria used in making this decision goes back to the purpose of the simulation. Spending some extra validation effort in the high AOA regime will insure that the simulator accurately represents the aircraft and will enhance the safety and productivity of the testing. However, spending significant validation effort in the heart of the flight envelope may not be worth it.

Another area of concern is validating the simulator with the pilot in the loop during a closed-loop task. Because of the great number of variables associated with closed-loop simulations, it may be virtually impossible to validate the complete flight envelope. Once again, examining the areas of highest interest will help narrow the focus of the validation effort. If the test team is very concerned about aerial refueling characteristics, then a significant amount of time should be spent validating that piece of the envelope. One of the techniques to accomplish that include replaying a pilot's input from an actual flight into the simulator. Still, whether or not the simulator will have the same look and feel as actual aerial refueling task depends on factors such as the visual scene and the whole simulator environment.

Eventually there comes a point of diminishing returns where it does not make a difference how much effort has been spent on validating a simulation. The test engineer must be willing to stop a validation effort if it appears to be stalled or not making quick enough progress. If the simulator cannot be validated at a particular piece of the test envelope, then the test team should take precautions to increase test buildup or proceed at a slower, safer pace.

There is no magic answer on the sufficiency of the validation effort. It is up to the judgement of the test team to decide when a simulation has been sufficiently validated. Understanding the simulator's purpose and utility is the first step in limiting the validation effort to something realistic.

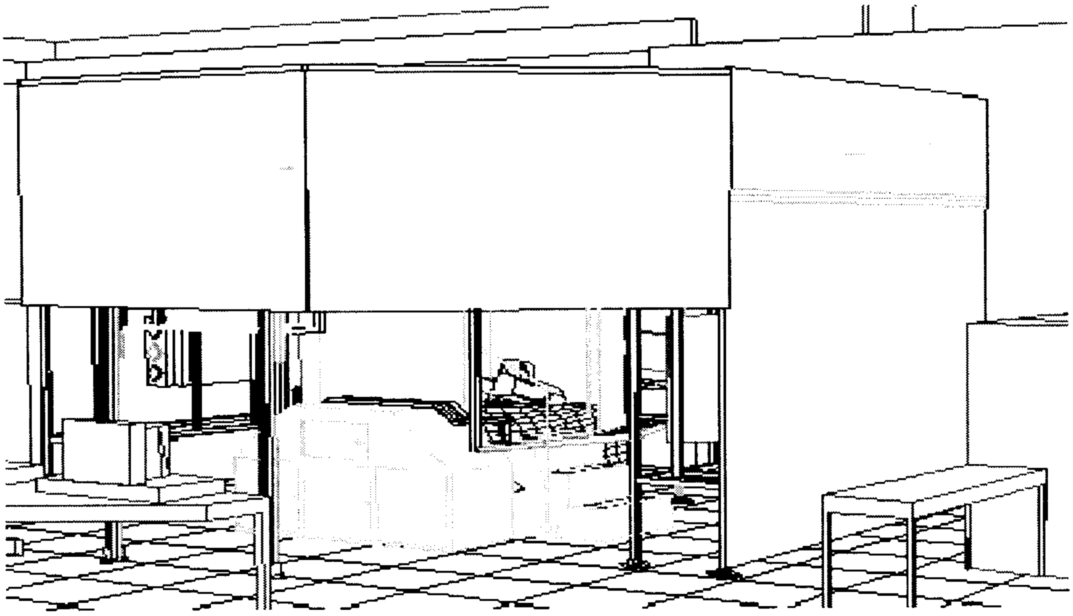


Figure 4-1

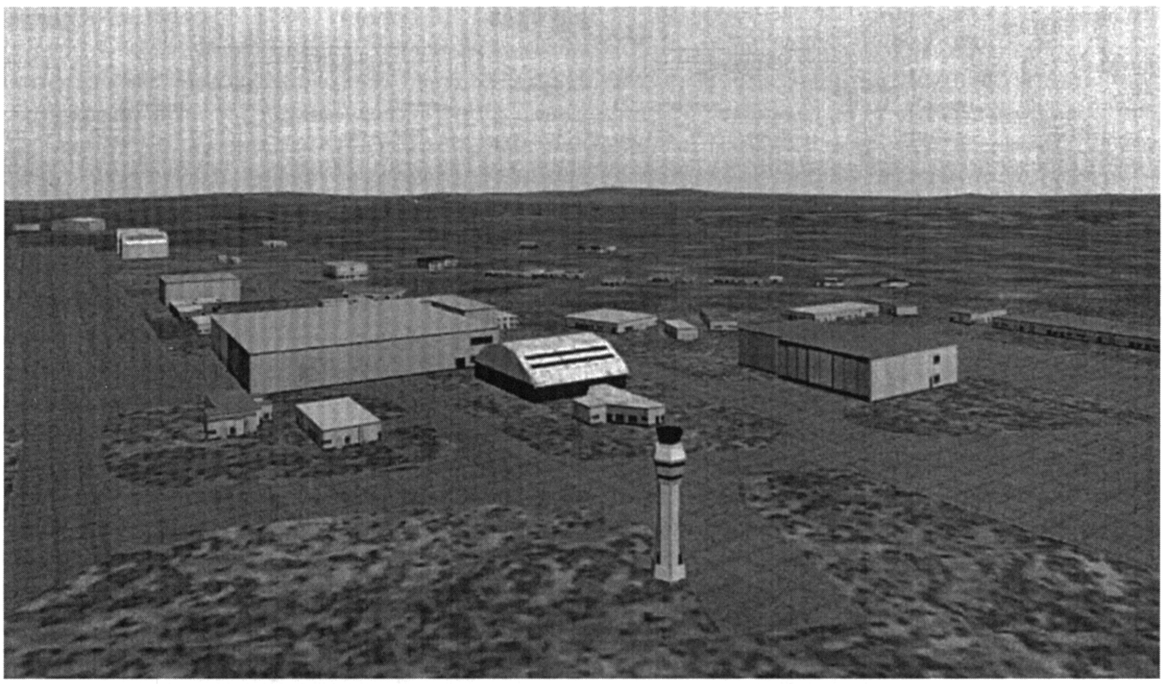


Figure 4-2

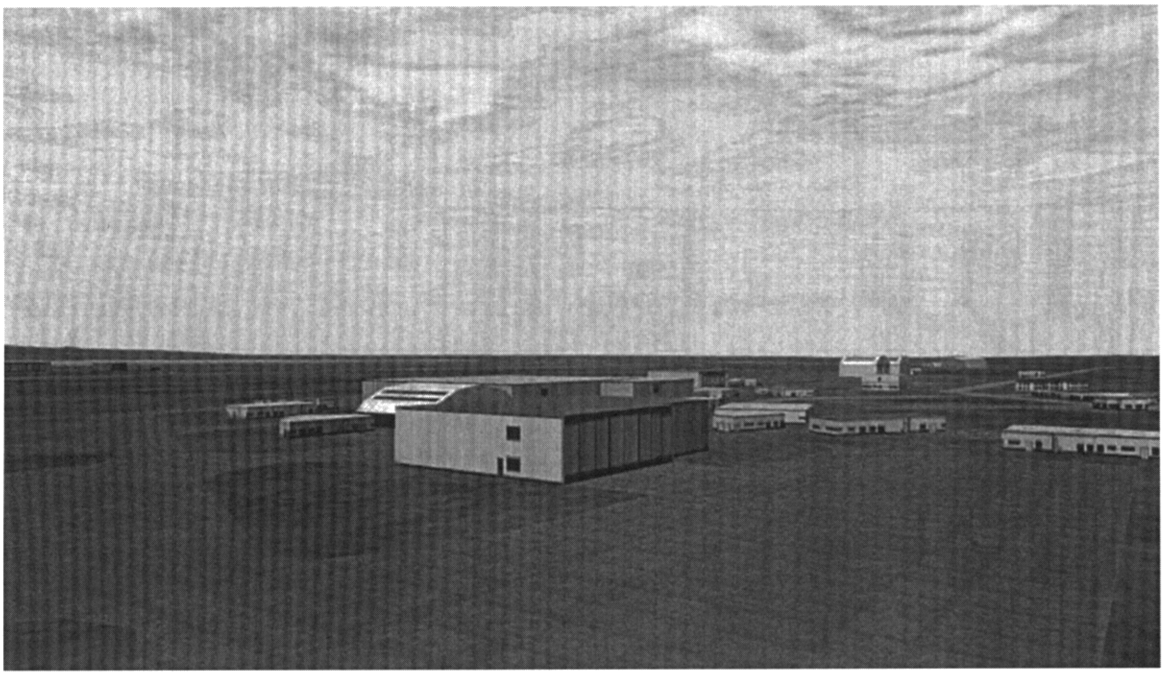


Figure 4-3

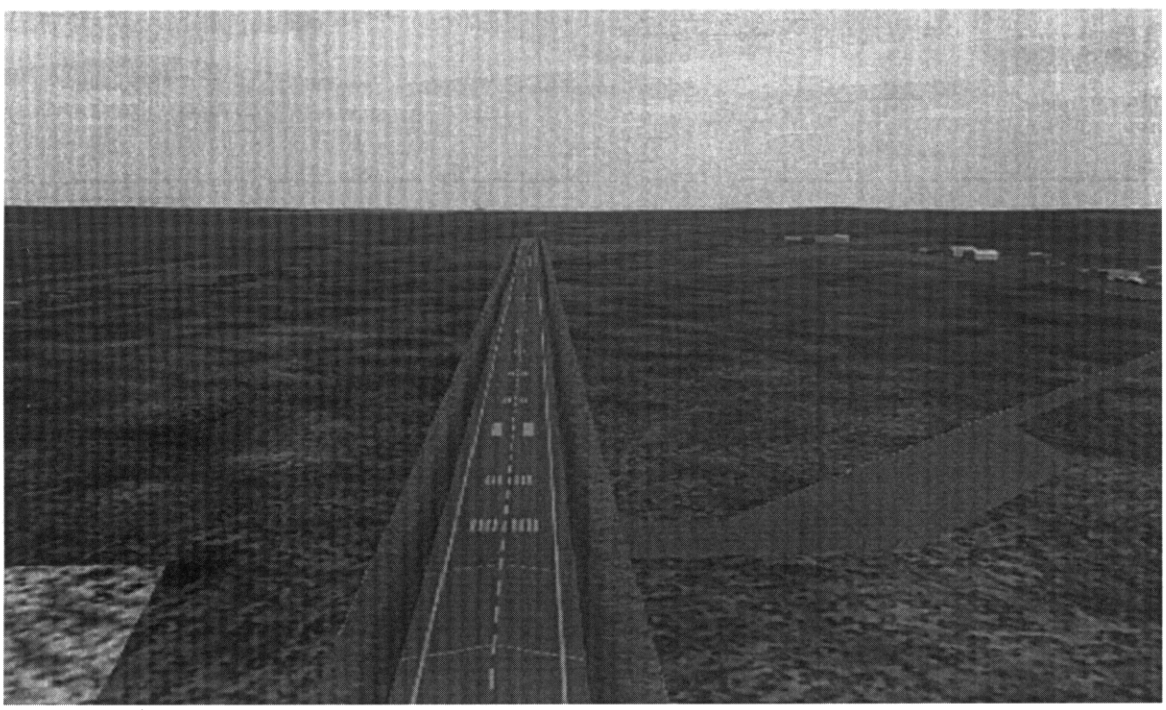


Figure 4-4

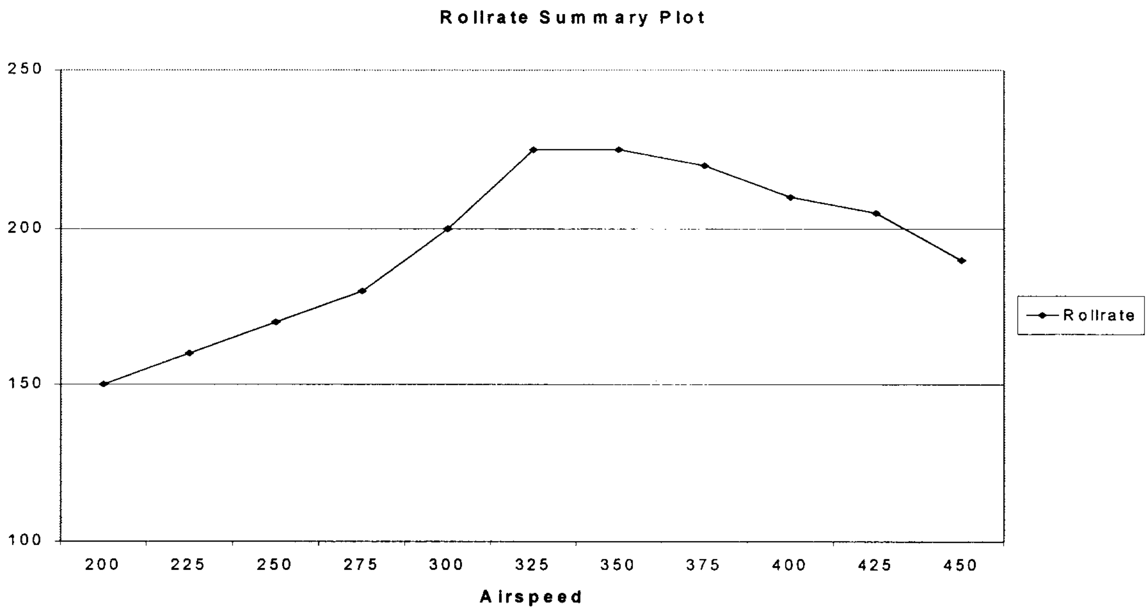


Figure 4-5

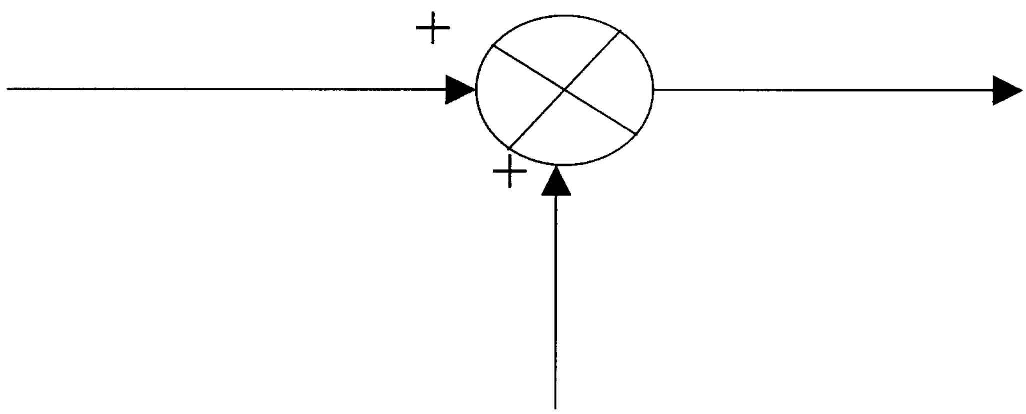
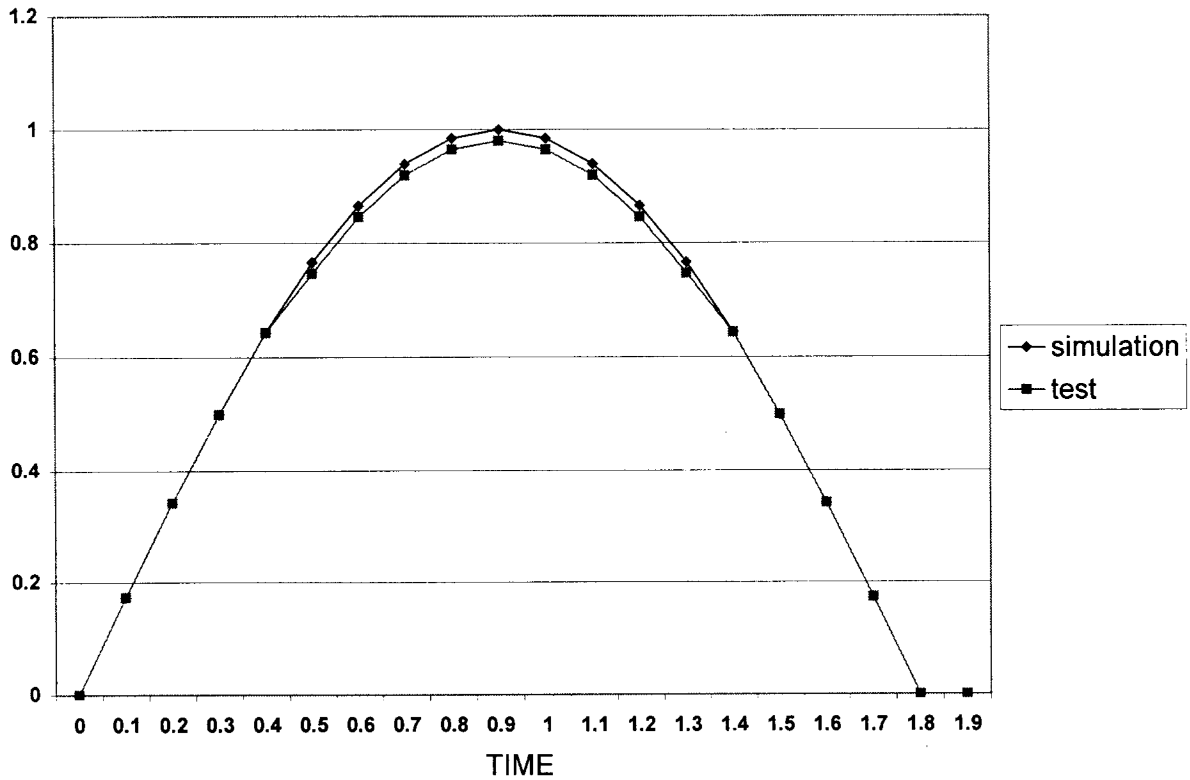


Figure 4-6


1.2
1
0.8
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0
0
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0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
TIME
simulation
test

Figure 4-7

5. CONDUCTING A SIMULATION BASED TEST PROGRAM

Integrating simulation into a test program requires forethought and planning. Figure 5-1 provides a generic flow of the steps to use simulation in support of flight testing. This section will discuss some of the considerations and factors that a flight test engineer needs to keep in mind when designing and using simulation as part of the test program.

5.1 Determine Test Objectives

As discussed throughout this document, determining what to test and then applying that to the simulator is the first step in the process. Not all flight dynamic testing requires a dedicated simulation. In deciding whether to build a simulation, the test engineer must consider the complexity of the test and the role that the development contractor's simulation will play in the testing. For example, flight dynamics tests that involve clearing the flight envelope of an aircraft carrying a new weapon, usually do not require a dedicated simulation. The additional weapon will probably have marginal affects upon the flight characteristics of the carriage aircraft. Any flight impacts are usually found during the design and integration of the weapon to the platform. The development contractor will have a good understanding as to which portions of the flight envelope may be degraded based on the addition of the new weapon. From this information, the test engineer can build a test program without the assistance of a simulation.

The are some types of tests where a simulation capability is a major asset. Major changes to the aircraft's flight control system, significant modifications to the aircraft's basic structure, or the addition of a new weapon that is so radical in shape that it causes the flight characteristics to change dramatically. In these cases, the test engineer should push hard to have a dedicated flight test simulation. The minimum required is an analytic, non real-time simulation. This provides the test engineer a tool to help define the test conditions and obtain some predictions that will minimize the safety considerations.

For new aircraft, experience has shown that having a dedicated, test simulation capability is essential to supporting a rapid fly rate and to significantly reduce the safety concerns. For brand new aircraft, investing in an in-flight simulation capability is also a wise choice. The object for using all of these various simulations is to insure the pilot understands the complexities of the aircraft before flying it for the first time. The test team may also want to build a simulation that can reside in the test control room. This will enable the test program to proceed at a quicker rate and enhance the safety-of-flight.

5.2 Build Simulation and Conduct V&V

Understanding the test objectives will lead to the type of simulation that should be constructed. One of the first considerations is to determine where to obtain the models for the simulation. Will the models be supplied by the contractor, or will the simulation engineer have to build the models from contractor supplied documentation? The fidelity of the models need to be determined as well as the data that will be collected from the simulation. This data needs to correlate to the instrumentation parameters being taken from the airplane.

Another consideration is the fidelity of the cockpit. Low, medium and high fidelity cockpit configurations were discussed earlier in the document, and their relationship to the tasks being required. Additionally the type and fidelity of the simulator visual system must be considered at this stage in the process. These factors should be a joint decision between the test engineer and the test pilot. Cost becomes a tradeoff variable in this decision process. The higher the fidelity of the cockpits and visual system, the more expensive the simulation will be to build and operate.

Special simulation considerations must be taken into account at this point. Will the simulation have to interface with the flight test control room, will it "shadow" the actual test aircraft? What format should the simulation data be in so that it is compatible with post-test analysis software and real-time control room display software? These must be specified to the simulation engineer so that these factors can be melded into the simulation design.

Also at this time, a preliminary plan for V&V should be constructed. The simulation engineer should provide the test engineer a plan on how the verification will be conducted and the length of time it will take. The test engineer then needs to layout the validation plan. This plan must take into account where the data will come from that will be used to validate the simulation. If this is a new aircraft, then the development contractor simulator data will have to suffice until actual flight test information is available. The test engineer must design the validation plan to expend the most amount of time in the areas of the flight envelope that are the greatest concern and which will use simulation as a basis for testing. Some of the typical areas are high AOA, takeoffs and landing, and the corners of the flight envelope. Although the whole flight envelope must be validated, not all needs to be validated with the same rigor. This is discussed in more detail in the V&V section of this document.

While the simulation is being developed, the test engineer should use the time to develop a test matrix that will be run using the simulation once it is developed. The test engineer should also be available to answer any questions from the simulation engineer regarding system performance. The first uses of the simulation typically employ the simulation in a non real-time or batch mode, even if the simulation was built to be an engineering MITL simulation.

5.3 Conduct Simulations to Determine Test Planning Matrix

By the time the simulation is finished and validated, the test engineer should have already developed a preliminary test matrix that will be used to satisfy the test objectives. What the engineer needs to know now, is whether these tests will meet the objectives, and whether the data points will fall within areas of the test envelope that needs further exploration. The engineers will do this work using analytic simulation as their primary tool.

Based on years of experience, the test engineers usually have a good initial concept of the magnitude of the flight test program. This knowledge provides a starting point from which to conduct the analysis. The strength of analytic simulations is the ability to examine a broad spectrum of flight conditions very rapidly and without a lot of assistance. An analytic simulation run in batch mode enables the engineer to input a large number of runs at once and then wait until the simulations are finished to begin examining the data. For example, if the stability and control (S&C) test engineer is interested in determining the aircraft's maximum roll rate at various portions of the test envelope, the engineer can do a batch simulation at flight conditions of 30,000 feet in increments of .01 Mach Number (M) from 0.2M to 0.95M. Once the simulations are complete the engineer may plot the results to help him visualize the trends. What the engineer is looking for are trends or anomalies that could indicate areas of particular interest that may need to be pursued during flight testing. Carrying the roll example further, suppose the data indicates that for some reason the graphs indicate a significant reduction in roll rate between 0.6M and 0.8M. Previous experience may have flight test points being accomplished at exactly 0.6M and 0.8M. However, because the simulation showed an anomaly in-between those ranges, additional test points may be added to gather additional data during flight test.

Of course, additional test points are not just automatically added if an anomaly is identified during simulation test planning runs, but this is where the test engineer can make a valuable contribution to the success of the whole program. Continuing the roll example, the test engineer should first check the simulation for problems and probably rerun the simulation to verify the results. Confident the simulation is correct, the test engineer should bring the problem to the attention of the other design team members. Subsequent investigations could reveal a problem in the aerodynamic data or a problem with the flight control system, or some other contributing factor. As a result, an important change could be made to the aircraft's or its subsystem design. Eventually the roll test points between 0.6M and 0.8M may or may not be flown, but by doing simulations to plan for tests, the test engineer has made a valuable contribution to the whole program. Besides looking for anomalies, the engineer uses the simulations to optimize the test program across the flight envelope. This optimization process entails attempting to meld several disciplines flight test requirements into an efficient program. As an extreme example, suppose the structure's engineer wanted to do a test point at 0.72M, the S&C engineer at 0.75M, and the engine performance engineer at 0.77M. Instead of doing all three test points, a common Mach Number would be picked and the respective discipline engineers would run simulations to verify the common test point still satisfies their needs.

The test engineer needs to balance the simulation results against the test objectives. If some test objectives cannot be met because of technical concerns, then the whole team needs to reevaluate those objectives, and if still required, then the aircraft may need to be modified in some way. The concept of this step is to insure that the tests can be done and that they are optimized to obtain the necessary data. This step can last months or years depending on the complexity of the tests, and it may be closely intertwined with the system design process.

A preliminary test plan should be the result of this process. This plan then needs to be looked at from the safety and pilot's perspective to factor in additional maneuvers or considerations that could impact the test program

5.4 Develop Test Maneuvers and Safety Considerations

This step of the process brings the pilot into the picture. By now the simulator cockpit has been completed and validated so that it accurately represents the aircraft's cockpit. The types of tests that can be done using an analytic simulation usually involves open loop testing where aircraft response to an input is being analyzed. However, the test pilots must still accomplish these open-loop maneuvers in the aircraft as well performing closed-loop maneuvers. The outcome of this step is a set of defined maneuvers that can be performed by a pilot, and gaining an understanding of any safety issues that must be accounted for during flight testing.

Typically, the open-loop tests are the first thing the pilot looks at. The pilot will try and provide an input at the appropriate rate and magnitude to satisfy the engineering requirements. This will also give the pilot a look at the aircraft's responsive or sluggishness to an input. This enables the test pilot to form an impression in his mind that he can compare with during an actual test. The pilot will also let the test team know if the they are asking for impossible flight conditions or inputs. The pilot may also suggest an improved method for conducting the test points in a more efficient manner. The test team should look at the fuel flows required to conduct the test maneuver and then try to determine if the maneuver can be conduced in association with other maneuvers.

The real benefit of having the pilot in the loop is to have him fly those test points that require his skills. These can be test maneuver such as constant "g" windup turns, high AOA maneuvering, closed-loop tracking tasks, or takeoff and landing tasks. These maneuvers usually touch the corners of the flight envelope and they are also some of the most hazardous tests to conduct.

The high AOA region is particularly well suited for piloted simulation evaluations. Due to highly dynamic conditions associated with high AOA testing, it may be impossible to replicate these tests using an analytic simulation. Besides evaluating the aircraft's response, the pilot may work out procedures to recover from out-of-control conditions. Executing the precise maneuver to enter a high AOA condition requires practice and timing. The simulator is the perfect tool to work out these procedures and to determine if there are safety considerations that must mitigated.

Additionally, closed-loop handling qualities maneuvers can be executed in the simulator. One of the areas that is closely scrutinized is the takeoff and landing regime. The pilots will want to get a feel for the aircraft in these configurations. Part of the challenge for the test engineer is to develop a task that will drive the pilot's gain up so that any undesirable flight characteristics will be noticed and can be corrected by the design team. Offset landings, or pinpoint landings are excellent tasks to force the pilot into the loop for landing. Of course, as discussed previously, having a high fidelity visual scene is critical if this task is to be successfully accomplished in a simulator.

From all of this pilot-in-the-loop work, the test team must make an assessment of the safety of the aircraft to proceed forward. Any undesirable characteristics should be noted and investigated. Additional analytic runs may be necessary to pinpoint a particular area that is causing the problem. If, for example, a high AOA test cannot be successfully accomplished because there is no method to recover from an out of control flight condition, then the test team must work with the designers to develop a fix or to placard the aircraft until a fix can be implemented. A placard against the aircraft will certainly effect the team's ability to meet all of the test objectives.

5.5 Conduct FMET

The next step in the using simulation to support flight testing is to bring the actual hardware into the loop. Typically, this means connecting the actual flight control system boxes that contain the actual flight control system software. A complete description of a HWIL simulator is discussed earlier in this report. FMET tests must be done with a HWIL. These can be done with or without a pilot, but if the objective is to look at transients and determine the handling characteristics with a degraded flight control system, then a pilot is required.

These tests are usually the last simulations that are required to be performed to verify that the aircraft is safe to fly. The object is to put the aircraft various situations and then induce a failure of some sort. The pilot will observe the transient and then evaluate the aircraft's handling characteristics to insure that it is safe to continue to fly. These tests are performed across the flight envelope, but the interest lies in the most hazardous areas such as high AOA and takeoff and landing. The pilot will also help work out emergency checklist procedures to cope with the failure.

The test engineer's responsibility is to insure that the myriad of failure modes is mapped into a test matrix that will provide the greatest insight on system performance in the shortest amount of time. The test engineer must also insure that any safety issues are resolved before proceeding on into flight testing. The engineering staff should be part of the team that is involved with the conduct of these simulator tests.

5.6 Train Test Team

One of the last steps to be conducted before beginning flight testing is to train the whole test team. Experience has shown that the whole team, pilots and engineers, need training together as a team in order to minimize mistakes. There are two methods for getting training, one is to use the ground simulator, and the other is to use an in-flight simulator.

5.6.1 Simulation Training

Ideally, the simulation facility should be configured as close as possible to the actual flight test control room layout. The team members should be performing their functions that they will have to accomplish during the actual test. To enhance the realism of the training experience, actual test cards should be created and distributed to the test team members. There should be an actual pre-flight briefing where the test is discussed with all team members.

The tests in the simulator should be conducted as if doing actual flight. If the simulator supports it, actual taxiing and pre-takeoff routines should be followed. The whole test card should be followed as written. Control room discipline and radio calls should also be done to insure maximum realism.

After the flight, a debrief should be done to not only look at the simulation results, but to go over procedures and weaknesses that may have perceived by the team members.

This kind of training needs to occur on a regular basis during the whole test program. Periodically refreshing everyone's memory regarding proper procedures and team relationships will continue to enhance the safety of the overall test program. These reviews should also be conducted if a new member of the team is introduced.

5.6.2 In-flight Simulation

An in-flight simulator is far more than a training tool. It can provide valuable information regarding a simulated aircraft's handling characteristics that cannot be obtained from a ground-based simulator. The in-flight simulator provides excellent training for the test pilot. Because of the motion cues, the pilot is able to get an excellent feel for how the aircraft will handle in an up and away mode or in a landing mode.

The in-flight simulator also provides a source of data that can be compared against the ground-based simulator. The pilot is able to translate what he sees in-flight and compare it to what he has seen in the simulator.

5.7 Compare Test Results and Update Simulation

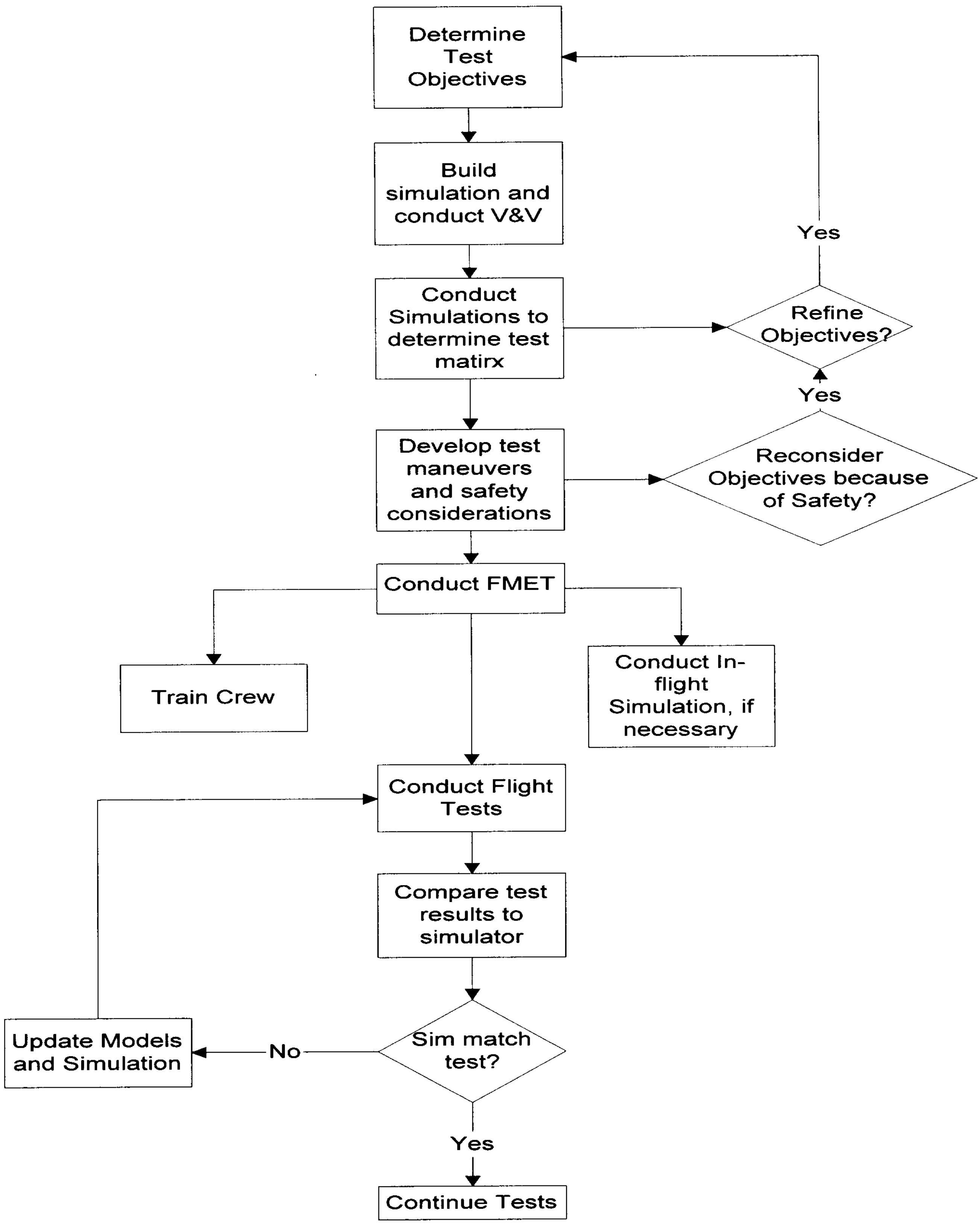
Now that all the simulation has been conducted, it is time to begin the test program. Prior to the first test flight, the test engineer must have developed a comprehensive set of predicted results that can be used to compare against the aircraft's actual performance. As mentioned earlier in the document, this data can be on graph paper or displayed on graphics terminals in the control room. The important point, is that the engineer is prepared to compare actual test results against the simulator predictions. Being able to do this comparison in real-time during the actual testing is a great advantage in terms of flight safety and speed of testing.

After each flight, the test engineer should do an analysis of the simulator data versus the actual test data. The engineer is looking for obvious discrepancies between the data or trends in the data, or other signs that may indicate that it is not safe to continue until the predicted data matches the actual test data.

The test team may need to use the simulator to resolve anomalies if they occur in-flight, or to restructure the test points depending on the actual data results. This is the most compelling argument to have the test simulation located in close proximity to the test team. If they are not co-located, then precious time could be wasted in travel time, and that could impact the progress of the program.

If the simulator and the flight test do not match, then steps must be taken to determine which one is correct and which one needs to be modified. Short of instrumentation or some other kind of system failure, it should be initially assumed that the simulator must be updated to match the actual test data. A description of this process is addressed in a previous section of this document.

If all of the predicted simulation data matches the flight test data, then the tests should continue onward. As the test program progresses, the test team will gain more confidence in the validity of the simulator, and may even find new uses for the simulation. Whatever the case, simulation is a powerful tool that improves and enhances flight testing. If the decision is made to invest in a simulation capability, then the test team must make maximum utility of the tool.


Determine Test Objectives
Build simulation and conduct V&V
Conduct Simulations to determine test matirx
Refine Objectives?
Yes
Yes
Develop test maneuvers and safety considerations
Reconsider Objectives because of Safety?
Conduct FMET
Train Crew
Conduct In-flight Simulation, if necessary
Conduct Flight Tests
Compare test results to simulator
Sim match test?
No
Update Models and Simulation
Yes
Continue Tests

6. FUTURE DIRECTION OF SIMULATION

The use of simulation is becoming more prevalent than ever. It is becoming a staple of aircraft manufacturers. As stated in a technical paper providing and overview of the Boeing 777 simulation effort (Reference 3), "The process of commercial aircraft design substantially benefits from and is entirely dependent upon high fidelity real time engineering simulations." The 777 program has been lauded as the wave of the future for airplane design and testing. The success shown by the 777 program has energized both the commercial and defense industries to reengineer their practices with regards to simulation. The United States Department of Defense is advocating a new process called Simulation Based Acquisition (SBA) as a method for significantly reducing the cycle time required to develop a new system. SBA provides a life-cycle approach that integrates simulation into the whole process from initial requirements, into design, test, manufacturing, and finally into the operations and sustainment of that system.

The continual increase in computer performance coupled with the decrease in price of computers has opened the doors for a proliferation of computer simulations unparalleled in our age. With computers on the desktop as powerful as big mainframes from a decade ago, the simulation tool can be brought directly into the environment in which engineers work. Additionally, the OTW visual scenes used in MITL simulations continues to improve dramatically. This too is driven by quantum leaps in graphical computer performance. These improved visual systems open up a whole spectrum of simulation not typically done previously. Data gathered during flight dynamics flight testing can be used as the basis to validates models and simulations that represent more aggregated pieces of the weapon system. Ultimately, the simulations will be sufficiently capable to allow for real-time analysis of the effectiveness of the system.

Another emerging trend is the drive to provide a common modeling and simulation architecture. The concept behind this trend is that if model developers build all of their models using the same architecture then these models could be reused from simulation to simulation. For example, a jet engine manufacturer would build an engine model using a common architecture and then that model would be given to all airframe manufacturers who need to use the engine model. Of course the simulations at the airframe manufacturers would have to be compliant with the standard architecture in order to use the model. Having a standard architecture would promote model reuse and reduce the costs of developing simulations.

If this trend materializes, it will be good for the test engineer who needs to build a flight test simulator. The test engineer relies on the models that were developed to support the design. Being able to take a model and easily integrate it into a simulation will save time and money. The model would already be validated, so the test and simulation engineers would just have to validate the integrated simulation.

The difficult part of this scheme is to establish a modeling standard and an architecture that all parties will agree upon. Many airframe manufactures consider their M&S capabilities to be proprietary thereby giving them an advantage over their competitors. However, within the United States DoD there is a considerable push to develop this kind of standard M&S architecture. Whether this trend will catch on will depend on the real usefulness of the architecture and its acceptance.

Complimenting the trend towards a common M&S architecture is the desire to link simulations together. For several years, there have been studies to determine the test usefulness of linking simulators together. A number of successful demonstrations have been conducted between the United States and Europe, but these have been focused primarily on the training aspects of M&S. The United States DoD has mandated that the High Level Architecture (HLA) will be the standard for the DoD when linking together simulations. Yet, no conclusive work has been done to validate that linking simulations together will benefit the test community.

Most simulation applications that support testing are real-time. Linking remote facilities together through encrypted communications paths induces some time delay. This time delay, even though it can be small, may be large enough to skew the simulation results. Studies are currently underway all over the to help determine the test utility of linking together simulations. While there appears to be some benefit for tests that involve electronic warfare systems, no data has shown that linking will improve flight dynamics simulations.

Simulation will become an ever increasing piece of the test picture. The test organizations need to plan on this trend continuing and to begin to develop or retain the expertise needed to create high fidelity simulations. At Boeing, this is considered to be a core competency within the company. Test engineers must continue to use simulation as one of the tools available to conduct flight testing, and they must accept and deal with the fact that there will continue to be a push to replace as much live flight testing with simulated testing. The simulation field is a burgeoning area and the test engineers must understand and embrace it so they can use it for their advantage.

7. CONCLUSIONS

Simulation has been an integral part of fight dynamics flight testing since the 1950's. For decades, the science of simulation was essentially stagnant until the revolution in the computer industry began in the 1970's. Since then, simulation has become an increasingly important piece of the flight test picture. Five primary types of simulations were discussed in this document: analytic/non real-time simulations, Engineering/Man-in-the-Loop simulations, hardware-in-the-loop simulations, iron bird simulations, and in-flight simulations. Each of these simulations are unique in their capabilities and support one or more of the six main purposes of flight test simulation. Those purposes are: test planning and flight envelope clearance, test maneuver practice and definition, verification and validation of software targeted for flight control systems, aircraft failure modes and effects testing, flight test crew training, test scenario development.

Simulation is a key tool in flight testing. Understanding the test requirements is the most important factor that will lead to a robust simulation that will meet the needs of the whole test team. These factors determine the complexity, fidelity, and utility of the simulation. However, the simulation is only as good as the models that comprise it. Inadequate data from which to build the models will result in a simulation that may not meet the test program's requirements. The test engineer may want to build a high AOA simulator, but without sufficient aerodynamic data, the simulation will not be much use in the flight test program. Verification and Validation of the models is an important step that must be done accomplished with rigor. Without proper validation, the flight test engineer may not be able to use the simulation to support flight testing.

There are many factors to consider that must be traded off in developing and using a flight test simulator. The advances in out the window visual scenes has expanded the use of the simulation but also increased the cost. While it would be ideal for every simulator to have a high fidelity visual system, the test requirements may not justify the expenditure. Still, even simple visual systems have provided a significant increase in visual capability and have given the test engineer more flexibility in designing a simulation test program. Thus, the visual system must be tailored to fit the designed use of the simulation.

As the use of simulations become more prevalent, there is a push to substantially reduce or eliminate the need to do any flight testing at all, and to just rely upon simulation to clear the flight envelope of the test aircraft. This is a dangerous trend that must be examined closely before proceeding too far down the path. The models that comprise the simulations are only as good as the data that has been used to develop them. There are still regions of the flight envelopes that require assumptions when building the models. The high AOA region is an example of this. Wind tunnels technology is improving and so is Computational Fluid Dynamics methods. But these technologies are unable to fully predict what is going to happen when an airplane is flying at very high angles of attack. Besides modeling deficiencies, the value of having the pilot fly the aircraft and get the cues from inside the cockpit can never be duplicated no matter how complex the simulation. Simulation will continue to be tool used to support flight testing and should not be used as a substitute for flight dynamics flight testing.

8. REFERENCES

1. Leigh, A.W., "Real Time Software for Small Computer Systems", Chesire, UK, Sigma Press, 1988.

2. Schilling, Lawrence J., and Mackall, Dale, A, "Flight Research Simulation Takes Off", Aerospace America, August 1993.

3. Williams, George, B, "The Boeing Commercial Airplane Engineering Simulation, New Airplane Project, Management Observations", AIAA-97-3794.

4. Andrews, Ian, "Keynote Address", in "Second Test and Evaluation International Aerospace Forum," London, UK, June 1996.

5. Boeing Commercial Airplane Company, "777-200 Fact Sheet", February 1997.

6. Patenaude, Anne, et. al., "Study on the Effectiveness of Modeling and Simulation in the Weapon System Acquisition Process," Science Application International Corporation, Test, Evaluation, Analysis Group, October 1996.

7. Brain, C.J., Clayton, T.D., Ward, N.J., "Organising Safety-Related Aircraft Simulation,: in "Second Test and Evaluation International Aerospace Forum," London, UK, June 1996, AIAA-96-3331.

8. Eddowes, Edward, E., and Waag, Wayne, L., "The Use of Simulators for Training In-Flight And Emergency Procedures", AGARDograph No. 248, June 1980.

9. Leclere, M., "Piloted Simulation and Airborne Navigation Weapon System Development Competition of synergy with Flight Test," June 1996, AIAA-96-3333.

10. Flight Mechanics Panel Working Group 16, "Aircraft and Sub-System Certification by Piloted Simulation", AGARD Advisory Report 278, September 1994.

11. Smith, T.D., "The Use of In-Flight Analysis Techniques for Model Validation on Advanced Combat Aircraft", in "Second Test and Evaluation International Aerospace Forum", June 1996, AIAA-96-3355.

12. Clarke, Robert, et.al., "X-29 Flight Control System: Lessons Learned", in "Active Control Technology: Applications and Lessons Learned", AGARD CP 560, January 1995, Paper 12.

13. Chacon, Vince, et. al., 'Validation of the F-18 High Alpha Research Vehicle Flight Control and Avionics Systems Modifications", NASA Technical Memorandum 101723, October 1990.

14. Melgaard, P.L., "STOL/Maneuver Technology Demonstration Test Program", SFTE 3rd Flight Testing Conference, April 1986, AIAA-86-9762.

15. Hanke, D., et. al., "In-Flight Simulator ATTAS – System Design and Capabilities", in "In-Symposium for the 90's", Braunschweig, Germany, July 1991.

16. Franklin, Gene, F., et. al., "Digital Control of Dynamic Systems, 2nd Ed., Addison-Wesley Publishing Co., Reading Massachusetts, 1990.

17. Flight Mechanics Panel Working Group 10, "Characteristics of Flight Simulator Visual Systems", AGARD Advisory Report 164, May 1981.

18. Flight Mechanics Panel Working Group 20, "Piloted Simulation in Low Altitude High Speed Mission Training and Rehearsal", AGARD Advisory Report 333, March 1997.

19. Isermann, Rolf, "Digital Control Systems, Volume 1: Fundamentals, Deterministic Control, 2nd Ed., Springer-Verlag, Berlin, Germany, 1989.A

20. Franklin, Gene, F., et. al., "Digital Control of Dynamic Systems, Addison-Wesley Publishing Co., Reading Massachusetts, 1980

APPENDIX A

There are three methods to take when emulating a filter:
- Method 1: Numerical Integration
- Method 2: Pole-Zero Mapping
- Method 3: Hold Equivalence

What must be considered when designing a digital filter is the filter's stability and the ability to precisely control the filter.

Method 2, pole-zero mapping, is a relatively easy method to apply, however, it requires that the analog filter be represented in terms of poles and zeros. For this project, this method is inappropriate since the analog filters are represented by Laplace-transforms.

Method 3, hold equivalence, requires that discrete input samples be held until a continuous signal can be formed. This method relies on fixed sample sizes. To correctly approximate the sample size in a digital computer requires use of high order polynomials. The higher the polynomial order, the more accurate the approximation. A benefit to using this method is its ease of implementation into a digital computer. A drawback can be the difficulty in determining the correct polynomial to approximate the filter.

For this example, Method 1, Numerical Integration was selected. Under this method there are three ways to do the integration:
- (1) Forward rule
- (2) Backward rule
- (3) Trapezoid rule

The rule used for this example is the trapezoid ru!e. The trapezoid rule is also referred to Tustin's method, named after the engineer who first derived the method for use in digital filters. A complete derivation of this method is found in Reference 19. Tustin's method allows for easy mapping from the s-plane to the z-plane, and thus it is sometimes referred to as the Tustin transformation.

This numerical integration method was selected for this project because it has been successfully used the United States Air Force in converting analog flight control systems to digital flight control systems. Also, it is easy to implement on a digital computer by using difference equations, and it produces high fidelity results when compared to analog filters.

The following derivation is a short overview of Tustin's transformation. References 17 and 18 contain complete derivations.

The fundamental concept to the derivation is to represent the filter transfer function H(s), as a differential equation, and then solve the equation using trapezoidal integration.

Now suppose a filter is represented by

$$\frac{U(s)}{E(s)} = H(s) = \frac{a}{s+a} \tag{4.1}$$

Where U(s) is the output and E(s) is the input to the system.

This transfer function is equivalent to the differential equation

$$\dot{u} + au = ae \tag{4.2}$$

Now rewriting (4.2) in integral form

$$u(t) = \int_0^t [-au(\tau) + ae(\tau)]d\tau \tag{4.3}$$

Now integrating over some interval *KT-T*, where *T* is the sample size

$$u(kT) = \int_0^{kT-T} [-au + ae]d\tau + \int_{kT-T}^{kT} [-au + ae]d\tau \tag{4.4}$$

Now applying the trapezoidal rule, the resulting difference equation is

$$u(kT) = \frac{1-(aT/2)}{1+(aT/2)} a(kT-T) + \frac{aT/2}{1+(aT/2)}[e(kT-T)+e(kT)] \tag{4.5}$$

Defining the z-plane transfer function as

$$\frac{U(z)}{E(z)} \equiv H(z) = \frac{T}{2}\frac{z+1}{z-1} \tag{4.6}$$

The corresponding z-plane transfer function of (4.5) is

$$H(z) = \frac{a}{(2/T)[(z-1)/(z+1)]+a} \tag{4.7}$$

When (4.7) is compared to the form in (4.1) it is readily seen that *s* is transformed to the z-plane with the relationship

$$s = \frac{2}{T}\frac{(1-z^{-1})}{(1+z^{-1})} \tag{4.8}$$

Where T is the sample size or frame time.

This substitution in (4.8) is Tustin's method, or called the Tustin transformation. Every where there is an *s*, equation (4.8) can be substituted. The term z^{-1} represents a delay of one time frame. That is for every *s*, the corresponding discrete sample is one frame delayed.

Therefore the s-plane representations of control system components can be transformed into the discrete signal domain by use of the z-transform. Each place an s is found, equation (4.8) is substituted for the s. Employing this technique means that for each type of function found in a flight control system such as first and second order filters, integrators, washouts, they all need to be converted to the z-plane. To further illustrate, the following is a derivation converting a first order filter from the s-plane to the z-plane.

The s-plane transfer function for a first order filter can be described as the ratio of the output, X_o, to the ratio of the input X_i. Thus

$$\frac{X_o}{X_i} = \frac{As + B}{Cs + D} \tag{4.9}$$

Substituting equation (4.8) for each *s* gives

$$\frac{X_o}{X_i} = \frac{A\left[\frac{2}{T}\frac{(1 - z^{-1})}{(1 + z^{-1})}\right] + B}{C\left[\frac{2}{T}\frac{(1 - z^{-1})}{(1 + z^{-1})}\right] + D} \tag{4.10}$$

Simplifying the equation using algebra

$$\frac{X_o}{X_i} = \frac{2A(1 - z^{-1}) + BT(1 + z^{-1})}{2C(1 - z^{-1}) + DT(1 + z^{-1})} \tag{4.11}$$

Now combining terms

$$\frac{X_o}{X_i} = \frac{(2A + BT) + (BT - 2A)z^{-1}}{(2C + DT) + (DT - 2C)z^{-1}} \tag{4.12}$$

And multiplying through

$$(2C + DT)X_o + (DT - 2C)X_o z^{-1} = (2A + BT)X_i + (BT - 2A)X_i z^{-1} \tag{4.13}$$

The term z^{-1} is a delay operator. That is, for every time *n*, z^{-1} can be expressed as *n-1*. Wherever there is no z^{-1}, time is assumed to be a *t=n*. When this is substituted in a difference equation that can be coded is the result. Substituting this into the equation (4.13) and solving for X_o at time = *n*.

$$X_{o_n} = \frac{(2A + BT)}{(2C + DT)}X_{i_n} + \frac{(BT - 2A)}{(2C + DT)}X_{i_{n-1}} + \frac{(2C - DT)}{(2C + DT)}X_{o_{n-1}} \tag{4.14}$$

Equation (4.14) would be the equation coded into the simulation. *T* represents the frame time used in the digital simulation. The term i_{n-1} and the term o_{n-1} represent those calculations that rely on the previous result. Notice that the denominator is the same for all the terms in the equation. Equation (4.14) represents a generic first order filter in form of (4.9). Thus this could be applied to lead filters, lag filters, and lead-lag filters.

Similar type derivations can be made for the remainder of the common time dependent functions found in a simulation. Listed below are the s-plane transfer functions along with the corresponding z-transform equation which for those common functions.

A rectangular integrator has the form

$$\frac{X_o}{X_i} = \frac{1}{s} \tag{4.15}$$

This takes the z-transform form of

$$X_{o_n} = \frac{T}{2}X_i + \frac{T}{2}X_{i_{n-1}} + \frac{T}{2}X_{o_{n-1}} \tag{4.16}$$

A Washout filter is special type of first order filter. Its s-plane transfer function is

$$\frac{X_o}{X_i} = \frac{As}{Bs + C} \tag{4.17}$$

The z-transform of this is

$$X_o = \frac{2}{2 + DT}(X_i - X_{i_{n-1}}) + \frac{2 - DT}{2 + DT}X_{o_{n-1}} \tag{4.18}$$

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- Iron Bird
- in-flight

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