Seeking the Proper Balance Between Simulation and Flight Test

An AIAA Position Paper
the AIAA Flight Test Technical Committee and approved by the Public Policy Committee

Approved by the Board of Directors
1 October 1999

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EXECUTIVE SUMMARY

This paper examines the past and present roles of modeling and simulation (M&S) in lieu of, or in support of, the developmental engineering flight testing of aircraft and airborne systems. However, it should be noted that much of the commentary also applies to space systems. It posits that both M&S and flight testing are essential for efficient and effective development of such systems. It demonstrates, however, that the proper balance of the two must be based on sound engineering and programmatic analysis of their respective capabilities, benefits and disadvantages. At this time such a rigorous evaluation is rare, contributing to demonstrated or potential testing mishaps, poor development methodology, cost and schedule impacts, and deficient systems. AIAA recommends that a methodology for guiding the disciplined balancing of M&S and flight testing be developed and promulgated to avoid these outcomes and

improve the air and space vehicle development process. AIAA offers the expertise of its Flight Testing Technical Committee and applicable Technical Committees to aid in this development.

INTRODUCTION

Modeling and simulation (M&S) has been used, in one form or another, since the earliest days of manned flight. The simulation methodologies most often used today-computer-based mathematical modeling of complex vehicle functions under simulated conditions-have been in use since the early 1960s. These have included purely analytical simulations, those with man-in-the-loop using displays and inceptors for feedback, some with actual flight hardware in-the-loop, and both fixed and motion-based simulators. The use of this technology has grown with the complexity of present aerospace systems such that they have become indispensable development tools.

Simulations are most typically performed to study the interaction of modeled systems to judge the suitability of predicted performance, ensure flight safety, provide personnel training, and supplement flight testing of the vehicle. As the credibility of the simulations and the complexity of flight systems have increased, more and more reliance has been placed on such simulations as design and development tools. These help to avoid deficiencies in performance or design flaws that can prove costly to correct later and endanger the program viability. Likewise, simulations have found increasing use as the aerospace industry and its customers have sought to reduce the time required to field a new vehicle (cycle time reduction) and overall development cost. In doing so, the role of simulations to support and supplant some flight testing has also grown. These goals have recently become the center of industry and U.S. Defense Department management initiatives, with considerable attention and resources being directed at the expanded use of M&S in system development, testing, training, and operation.

The experience of the members of the AIAA Flight Test Technical Committee (FTTC) is that simulation is a necessary complement to flight testing, but that flight testing remains an essential element of sound air vehicle development. The current emphasis on expanding the use of M&S has been promulgated with the intention that it can help to reduce flight test time and cost, enhance test safety, and increase testing efficiency. The "model-test-model" paradigm is held forth as the most efficient combination of these development tools. In this paradigm the initial modeling and simulation guides the planning and conduct of flight testing, with incremental test results then used to enhance the accuracy and/or fidelity of the simulation before the process is repeated. (The paradigm has also been described as "model-test-compare-model," "predict-test-compare," and other variations.) The cycle would be repeated many times during the course of the test program, especially in an effort to avoid the "fly-fix-fly" paradigm that commonly proves inefficient.

PROBLEM STATEMENT

Although much of the leadership in the U.S. aerospace industry and Defense Department insist that M&S is not intended to replace flight testing, there remains concern among flight test practitioners that the result will be an overreliance on simulation. This has a potential for neglecting invaluable empirical test data verifying system performance. In addition, detrimental and potentially hazardous system characteristics may not be uncovered, and overall assessment of vehicle worthiness vis-a-vis its mission will suffer. Appreciation for a sound balancing of flight testing with simulation must be promulgated. In addition, a methodology appears to be needed to help insure this sound balance.

CONCLUSIONS

In reviewing the recent progress in human space flight and the studies for future human space exploration, the AIAA concludes that:

DEFINITIONS

The term "modeling and simulation" is taken to include:

- Digital models and computer simulations using those models
- Mathematical analytical tools such as Computational Fluid Dynamics (CFD)
- Simulated flight testing such as in wind tunnels and engine altitude test chambers
- Hardware-in-the-loop simulations
- Pilot-in-the-loop simulations, with and without hardware-in-the-loop
- In-flight simulation
- Other large-scale ground tests

Each of these initially employ simplified system representations that become more complex as the systems engineering process defines the system during the course of development and as test data becomes available to improve model and simulation fidelity and accuracy. Present initiatives are expanding the application of verification and validation of M&S resources to ensure that they function as intended and suitably (for each individual application) represent real-world behavior.

Flight testing itself can be considered a simulation if the test article is an experimental system or early prototype, if some internal or external system functions are contrived, and if test conditions do not truly match actual in-service scenarios (such as simulated combat). Operational test and evaluation (OT&E) flight test relies heavily on constructive simulation and pilot-in-the-loop (PITL) tactical simulations. All this has become more popular as simulation capabilities have increased and flight test budgets and schedules have decreased. However, the flight environment, with systems interacting and with a pilot (perhaps) in control, is not a simulation. Flight test remains the most dynamic and credible medium for collecting actual system performance data.

DISCUSSION

While this Information Paper principally uses air vehicle flying qualities to illustrate its points, simulators are also advantageous in supporting the evaluation of pilot-vehicle-interface issues, avionics performance, and reducing overall operational risk.

Historical Examples

It is reasonable to judge the successful application of M&S by comparing the actual performance of air vehicles, as revealed or substantiated through flight testing, with the performance predicted with M&S. Such an examination reveals that substantial design deficiencies or unanticipated system characteristics requiring correction continue to be revealed during flight testing despite the sometimes substantially and costly applications of M&S. Hence, the value of flight test has been repeatedly validated. In addition, the need to verify system performance through actual flight demonstration remains the most credible "graduation exercise" in the eyes of senior decision-makers, policy-makers, and users.

A compilation of historical examples, derived from documented accounts and personal experience of the FTTC membership, is included as the Appendix to this Information Paper. These show the value of flight test combined with sound M&S methodologies. They also show that the limitations of M&S tools continue to appear, sometimes to the detriment of programs despite the rapid advance of the M&S state of the art. An excessive reliance on M&S, even those subjected to comprehensive verification and validation, is unjustified given the continuously more advanced systems these tools are required to model.

The Benefits of Using Simulation

Simulation provides a design tool permitting increased understanding of the integrated system during design and before flight test. This helps to ensure that the system performs as required, aids identification and correction of design deficiencies, and helps to identify potential problems requiring test data. Simulation also enables an early evaluation/assessment of the system, both with and without actual flight hardware. The use of M&S reduces program risk and improves test planning. Simulation is a tool for verifying corrections of deficiencies discovered in flight before resuming testing. It enables conditions to be evaluated that are unachievable or too hazardous for flight test. But, many limitations on simulation remain. For example, high angle of attack and spin investigations are the most difficult simulation task, with separated flow making it difficult to verify the accuracy of the modeling. So, the high-risk flight testing for these investigations remains essential.

The routine methodology for using simulation during flight testing to resolve flight control instabilities has been well exercised in recent years. It begins with improving the fidelity of the simulation until the instability is reproduced. Revisions to the control laws or system components are then evaluated in the simulator to ensure that they correct the instability without producing other detrimental results. The new "build" of the flight control software is then thoroughly evaluated in the simulator and through normal software tests to ensure that it can be safely installed in the aircraft. Once the build is installed in the test aircraft, regression flight test is performed to ensure that the instability has been corrected and no new detrimental handling qualities have been introduced by the changes.

The ever-present need to simulate is accompanied by a need to validate the simulation by collecting actual performance data and then updating the simulation to ensure its fidelity and accuracy. The final model/simulation should accurately reflect the true system performance. This resulting validated model can then permit exploration of the system more extensively than in flight. It can also provide much broader and in-depth insight into system characteristics than a flight test report reflecting performance only at discrete test points.

As suggested here and demonstrated by the examples in the Appendix, the use of flight test and simulations are complementary in evaluating an air vehicle. This is true whether the evaluation is aimed at determining the safety of the vehicle, its performance, its readiness for production, or the maturity of new technologies. However the benefits almost always require validation through actual demonstration in flight, e.g. flight test.

Complementary Use of Simulation and Flight Test
The complementary benefits of integrating simulations with flight test include:

Prior to flight testing:

- A better understanding of the vehicle to determine prioritized testing needs.
- A determination of the required test data to reduce simulation uncertainty and validate the simulation.
- A determination of required test data fidelity and accuracy.
- The means of simulating test conditions and procedures to optimize testing, and support formulation of the most efficient test matrix.

During flight testing:

- A training and planning tool to optimize testing.

- A means of extrapolating test results to allow optimized testing and greater safety.
- A means of extrapolating test results to conditions that are unobtainable or involve unacceptable risk.
- A means of quality checking test data as it is collected.
- A means of injecting a signal or input into the system or test environment while testing in a "simulation-over-live" mode.
- Reduced regression testing.

After flight testing:

- Determine the significance of test results within the context of the system's entire performance spectrum and military worth.
- A validated tool representing the system more comprehensively than test data alone.
- A higher fidelity and accurate engineering tool to support the vehicle throughout its life.
- A training tool supporting follow-on testing requirements.

Present Simulation Limitations

Historically the relationship between modeling and flight test was the performance of initial simulation before progressing to flying. Recently the industry has gone from initial modeling to simulation, then to flying the vehicle, to validate the model by matching simulation, to revise the model and then fly again. This new paradigm implies that modeling and simulation is becoming increasingly integral to the overall test process. But time, cost, manpower, technology, and the ability to model complex system interactions continue to present limitations to the accuracy and fidelity of M&S. These limitations mean that flight test must continue to be an essential element of air vehicle development.

Air vehicles and systems can be represented by analysis and simulations to save time and reduce risk. For the example of flight control system (FCS) development, problems can be dealt with using non-real time simulations that represent the pilot by a mathematical model. The aircraft dynamics, structure flexibility, etc., can be represented at various levels of fidelity. Such a simulation can give initial pointers as to possible areas of concern, typically where desirable handling qualities may be suspect. In such cases simulation enables the effects of FCS changes to be assessed and safety improved. But, as FCSs are becoming more sophisticated, the challenge to predict potential handling problems remains. Results are only as good as the initial assumptions, model fidelity, and the other simulation limitations. At present even the most sophisticated simulation cannot guarantee that there will not be handling problems because of the complexity of simulating pilot behavior under different circumstances. This observation is born out by examples in the Appendix. Fixed-Base Simulators (FBS), with a pilot-in-the loop, are often used as a tool for an initial examination of flying qualities. In such cases cockpit displays and inceptors can be represented, and perhaps visual cues incorporated. Flight control system characteristics can be represented mathematically, or more realistically by a "hot bench" (actual flight firmware in the loop) or "iron bird" (flight control hardware in the loop via a physically representative rig). With such tools, valuable insight can be obtained into the possible design areas of concern. However, motion cues are non-existent. Some FCS dynamics (such as bobweight effects and system nonlinearities) can seldom be faithfully reproduced. These limitations may significantly impact the value of the simulation and resulting data, even with the pilot and hardware in the loop. Moving Base Simulators (MBS) can address the lack of motion cues. Pilot-in-the-loop simulation may be sufficient to represent cruise flight, but high-gain or high-g piloting tasks such as precision landings, in-flight refueling or air-to-air/air-to-ground pipper tracking tasks cannot be simu-lated well enough to provide complete confidence. This limitation is typically a result of simulator hardware bandwidth and responsiveness.

In-flight Simulators (IFS) largely remove the above limitations by flying a developmental FCS design in a surrogate aircraft. This provides visual and motion cues similar to the subject vehicle, and can more accurately measure pilot-induced oscillation (PIO) susceptibility. The IFS can be used to assess dynamic response (requiring variable-stability aircraft) or performance measurement such as low lift-to-drag ratio (L/D) which can be achieved by configuration changes to the testbed aircraft. However, system dynamics are seldom exactly those of the prototype article (actuator and other mechanical system dynamics are those of the surrogate aircraft, for example) and any structural feedback would be those of the surrogate aircraft. Any model errors will lead to incorrect results, especially if all six degrees of freedom cannot be realized. So, even the IFS results are limited in their applicability to the prototype system and have been used only as a precursor to flight test of the real developmental vehicle.

Even if problems are encountered in the simulator, warnings are not always heeded. Failure to act may be because the results are not trusted or because it is assumed that "the pilot would not really fly like that." The crash of the Saab Gripen test aircraft provided a dramatic example of what happened when PIOs were encountered in flight despite earlier simulations suggesting the potential for the instability (see Appendix). Likewise, problems revealed through the simulation may lead to significant design changes, yet be found in flight testing to have been a false indication. For example, the predicted propensity for a lock-in deep stall with the T-tail configuration was the principal reason for making the C-17A a fly-by-wire aircraft. Flight test demonstrated that the deep stall was not as great a concern as predictions suggested. In general, however, unnecessary design efforts invoked by incorrect predictions are much more difficult to document than design characteristics that were only revealed during flight test or in service.

The members of the FTTC are unaware of any study that has supported the claim of substantial program cost savings realized by a significant expansion of the use of M&S with a concomitant reduction in testing. While flight test is expensive and can be a lengthy process, the writing, testing, validating, and verifying of software can also be quite expensive as it involves many persons and expensive resources, and can take a long time to mature. Unlike flight testing, the credibility of a simulation may always be subject to doubt. Experience suggests that only a reasoned, complementary application of all these means will yield the best program results.

Perceived Need for Improvements

The Joint Strike Fighter (JSF) is to be a multi-role weapon system with conventional, carrier-borne and short takeoff and vertical landing (STOVL) variants, and with operational differences between the various models and operators. For such a future system, it is essential that the vehicle behave well in all operational scenarios if the affordability of the vehicle is not to be in doubt. The difficult task of integrating supersonic STOVL and carrier operations is essential for JSF success. So, simulation has to cover all of these aspects of the system. Tools such as CFD have already been used to back up extensive wind tunnel investigations in up-and away flight, STOVL, and Carrier Operations. Wind tunnel testing or CFD is still essential to set initial values for the modeling, which is then validated by flight test. But a demonstration/validation flight test is still considered an essential part of the program before commitment to detailed and costly weapon system development. The limitations of simulation are continually revealed through actual flight experience. Yet the ever-expanding capabilities of aerospace systems continually challenge our ability to model their behavior. The next generation of hypersonic vehicles and reusable launch vehicles will stretch simulation capabilities even further. For example, research efforts should be initiated to develop the kind of robust, predictive codes that are needed to really understand the phenomenology associated with local separated airflow during maneuvering and transonic flight.

Despite the continuing advances in simulation technology which are attempting to rectify past shortcomings, there continues to be a need to seek an efficient balance of the information which can be gained from models and simulations versus that which can only be obtained from flight test. But recent initiatives, investments and pressures have raised several important issues. How does the test community strike such a balance? What processes need to be put into place to assure that the model/test decision is based upon the total picture and not upon the bias of a particular advocate? What guidelines need to be developed so that model/test decisions are consistent?

CONCLUSIONS AND RECOMMENDATIONS

This paper has shown that the present emphasis on expanding the use of analytical M&S and ground simulation testing-in lieu of open air range flight testing of aerospace systems-holds a risk. This risk is that one source of system performance information will be judged more valid than other sources without a suitable balancing of the beneficial attributes of all three sources. This can be avoided by employing a process guide that will help in selecting, for each aspect of the system under consideration, the best source of performance information. This selection should consider: source accuracy, fidelity, suitability, credibility, maturity, cost, timeliness, availability, and similar characteristics. The process guide might consist of a series of questions to be answered for each information-acquisition source to allow for a weighing of related advantages and disadvantages. In this way, the most efficient and effective means, or combination of means, of collecting engineering data and program risk reduction information on the system can be determined without a misleading application of personal judgment and misinformation. Information illustrating the validity of these decisions should be collected during program execution to assist the next program. AIAA recommends that the above approach be adopted and that a process guide be developed for use in determining the balance between analytical M&S, ground testing and flight testing. AIAA offers the assistance of the Flight Test Technical Committee and other pertinent Technical Committees in the formulation of this process guide. AIAA also offers our assistance in the documentation and dissemination of the process guide so that it may have wide distribution including the potential for incorporation into course curricula at appropriate educational institutions.

For APPENDIX, LIST OF ABBREVIATIONS AND ACRONYMS, and CONTRIBUTORS, please contact AIAA at the above address.