FIGHTER AIRCRAFT PERFORMANCE MODELING, SIMULATION, AND FLIGHT TESTING FOR RESEARCH AND DEVELOPMENT

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ABSTRACT

Among the methods available for investigating in detail the performance of real or hypothetical fighter aircraft systems are a spectrum of simulation techniques ranging from pure computer modeling, on the one hand, to flight tests simulating combat operations, on the other. Intermediate between these techniques, in several senses, is simulation involving one or more pilots on line with a computer and display system, "flying" simulated aircraft in real time. Although all three classes of technique involve varying degrees of simulation, for ease of expression they are referred to here as modeling, simulation, and flight testing.

Each of these classes of technique contains a number of examples of varying complexity. Each class has its typical advantages and limitations and is most appropriate for certain types of investigation. A comparison among them is made on the basis of characteristics such as the following: degree of experimental control, ease of variation of parameters, range of parameter variability, cost per case, time required per case, realism, and credibility. The suitability of the three classes of technique is considered primarily in terms of their value for design studies and design evaluations, but references are made to other uses such as training and development of tactics.

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I. INTRODUCTION

Military research and development presents a number of fascinating problems to observers and participants in the process. Almost everyone involved expresses frustration at the slow pace of the events that transpire between conception of a new technical capability and production of an operational system that exploits it. And almost everyone has some notions, however well- or ill-conceived, as to how to speed up the process and/or achieve better end products.

Students of research and development see problems at a variety of levels of generality, from broad conceptual issues down through organizational techniques and contracting procedures to detailed questions of day-to-day operations and decisionmaking. The present paper deals with a type of problem at the detailed end of the spectrum, namely the appropriate use of certain methods of analysis for R&D decisionmaking. There are, however, in the argument presented here, some implications regarding larger issues of the R&D process.

The discussion herein of R&D investigation methods will be focused on fighter aircraft, although generally parallel arguments to those presented here could be based on examples from other types of systems. The

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methods we are talking about are three rather closely related techniques: pure computer modeling of fighter system performance, simulation involving one or more people plus computers and other hardware in the simulation loop, and flight testing. All three have been used or have been suggested for use as a part of the basis for decision in R&D for fighter aircraft systems.

DEFINITIONS

First let us define some terms. For present purposes, we use the term "computer modeling" to refer to a very specific type of computing. We are referring to computer programs that calculate in considerable detail the flight paths of one or a small number of aircraft and/or missiles. Many such programs exist, with varying degrees of refinement in the flight path computation.[1, 2] At one end of the scale are simple 2-dimensional models that calculate constant-speed, constant-turning-rate flight paths in the horizontal plane without explicit reference to aerodynamic and propulsion characteristics of the aircraft. There are some rather elaborate 2-dimensional models that do account for aircraft performance and for relatively sophisticated maneuvers. The ATAC model developed by Caywood-Schiller Associates for the Systems Engineering Group of the Aeronautical Systems Division is an example of the latter type.[3] Then there are 3-dimensional simulations with fine-grained representation of the aerodynamics, propulsion, and maneuvering tactics of 2 or 3 bodies. The TAC Avenger model (called FANTAC in an earlier version of the model), developed by North American-Rockwell's Los Angeles Division for Headquarters USAF[4, 5, 6] and the RAND TACTICS model[7] are examples. The latter is in use now at some 20 industrial and government organizations across the country.*

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*A basic characteristic of the models we are discussing is that their results are dominated by the technical performance of specific items of hardware. It is important not to confuse them with another type of model that has been used in various attempts to determine desired fighter characteristics, namely models of vast aerial operations such as entire multi-strike tactical air-ground campaigns or air-superiority battles. The campaign and battle models submerge all but the gross differences between performance of different types of equipment.

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Aircraft performance computer models are frequently referred to as simulations. However, for convenience in this paper we are reserving that term for techniques in which one or more pilots are in the loop, acting in real time to control the simulated flight paths. Such simulations characteristically imply full-scale cockpit mockups, sizable visual display systems, and large computing installations. Examples of such simulations are the prototype Manned Air-to-Air Combat Simulator[8] designed and built by the LTV Aerospace Corporation in Dallas, Texas, and the Simulator for Air-to-Air Combat[9, 10] which has been designed under the direction of the Aeronautical Systems Division and is presently planned to go into advanced development.

They require large number of inputs and assumptions as to hardware effectiveness, and calculate military operations according to a rigid and usually simplistic logic. Such models may possibly be of use in force structure or requirements studies, if handled with caution. In general, however, we tend to agree with J. A. Stockfisch's assessment of models of this type. He asks, "What have been the results of this rash of model building and computer simulations?" And concludes, "By and large, nothing useful. Most frequently, the analytical results have not been credible." Following a discussion of methodological and intellectual shortcomings of such models, Stockfisch urges that "they be discarded for the time being as a bad scientific joke."[11]

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II. SOME GENERAL CHARACTERISTICS OF THE METHODS AS R&D TOOLS

It is useful to identify distinctive characteristics of the methods from the point of view of their application to R&D problems. From these considerations we can suggest typical appropriate uses and point out instances in which methods appear to be misapplied. In general, the distinctions between the methods are quite straightforward.

EXPERIMENTAL CONTROL

Without question the computer modeling technique permits the greatest degree of experimental control, and flight testing the least. Control of variables is complete in modeling, since all inputs and operations must be made explicit for the computer. This also applies to models involving Monte Carlo routines, since the probability distributions are controlled by the programmer or user. The degree of control afforded by simulation techniques may be quite close to that provided by modeling, depending on the nature of human intervention in the control loop. Since mechanical aspects of a simulation, in a well-designed system, can be repeated exactly or varied in precise incremental steps, simulations can provide a unique basis for certain types of human factor and man-machine interface study that cannot be done in flight testing nor in modeling, such as coupling the dynamics of the aircraft with the response and judgment of a pilot.

PARAMETRIC RANGE

Again, modeling clearly provides the widest--that is, an essentially unlimited--range of parameters. Flight tests are limited by flight safety considerations as well as by the capabilities of existing flying hardware and instrumentation. Simulators are inherently limited by the simulator hardware, and it is, of course, possible and desirable to construct simulators with the capability of representing operations considerably beyond the limits of existing aircraft and other flight hardware.

CREDIBILITY AND REALISM

The order of preference among the three methods, on the basis of credibility and realism, tends to be the reverse of the order based on the factors discussed above, but the distinction is not always clear-cut. Obviously, all events and observations that occur in flight test can happen, whereas simulations and models can represent things impossible in the real world, so that tests have an unquestioned superiority of realism on the basis of what is possible. On the other hand, it is not always the case that flight tests provide more realistic data than the other two methods. One can easily construct or recall examples of flight tests that have been highly unrealistic in the sense that they did not represent real-world combat conditions. The lack of realism may be due to faulty experimental design or to hardware and safety limitations, or, in some cases, simply to misapplication of test results. Nevertheless, flight test results tend to carry a great deal of credibility. Sometimes they should, but often it is as necessary to be skeptical about the applicability of their results as about the applicability of models or simulations.

CALENDAR TIME

It can take a great deal of time to build and check out the equipment and software for any of the three mehtods, so that it is difficult to make a meaningful comparison except among fully developed methods. Once the tools are available, the speed advantage lies either with modeling or simulation, depending on the time required to prepare for, execute, and reduce the data from a particular experiment. Some aircraft performance computer models run at speeds several times slower than real time on current-generation computers, so that simulators (or even flight tests) may be faster for examination of single cases. However, in general, even the most complex computer model has a considerable overall calendar time advantage over simulations, and simulations have similar advantage over flight tests.

OTHER FACTORS

The question of time is closely related to that of cost, which will be discussed in the next section. Here we want to mention other aspects of these three different investigation techniques. In any research process, one can learn valuable lessons other than answers to the specific questions he is studying. Because the environment is most nearly complete in flight tests, tests offer the greatest possibilities for this kind of serendipity. On the other hand, the test pilot may be, but is not necessarily, closely coupled into the research program; and feedback into the learning process may not occur unless the experimenter and the researcher are the same person. The analyst inputting and studying the results of a computer model, even though he operates in an environment very lean in its mixture of operational realism, is so close to the study process that he may be able to profit greatly from insights into operational problems. Our point here is that any of the methods can lead to valuable unplanned learning. The richer the test environment and the more directly involved the researcher, the more likely this type of learning is to occur.

Another factor worth mentioning is the value of the three research methods for training. For this role, simulation and flight testing have considerable value, modeling very little. Models can be of some use in an adjunct to training, by providing a means of setting up useful exercises, but that is about the limit of their usefulness in this role. The utility of simulators in providing controlled, graduated training exercises, including simulated emergency conditions, is well known and need not be addressed here.

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III. COST CONSIDERATIONS

The facilities and personnel required to conduct a given study vary greatly among the three techniques. Since each has inherent limitations and advantages, it is apparent that direct cost comparison for a given investigation would apply only to a particular study and would be too specific in nature for this paper. Therefore, no attempt is made here to determine which of the techniques is best from a cost standpoint. The intention is to show the types of resources involved in each of the techniques and give some feeling for the relative costs.

MODELING

Of the three techniques considered, computer modeling requires the least amount of equipment and fewest personnel. However, it may entail the largest number of computing runs because of the parametric approach inherent in this technique. For example, system design characteristics may be systematically explored over a wide range, or a variety of tactics may be represented to cover the range of decisions a pilot could make.* The discussion on costs of modeling is based largely on the authors' experience with the RAND TACTICS model. Other five- or six-degree of freedom three-dimensional, multi-body models are expected to have similar cost characteristics. Two-dimensional models in use at RAND and elsewhere are considerably cheaper to run per case. The costs discussed here are somewhere near the upper limit for current fighter performance models.

The TACTICS model is presently being run on a two-channel IBM 7044 digital computer. For some of the larger, more complex modeling programs it appears that a third-generation computer (presently becoming operational across the country) may not only be desirable but necessary. For example, the TACTICS model presently is limited by the core capa-

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*It should be noted that in the other two techniques, simulation and flight testing, even expert pilots do not use the best possible tactics at all times, and multiple runs are required to obtain representative results. The need for multiple runs is accentuated if the "new" aircraft or weapon system differs greatly from the ones to which they are accustomed.

city of an IBM 7044 or 7094. On the IBM 7044, it can take up to 45 minutes to simulate 5 minute* engagements at a cost which varies between $200 and $280 per hour of machine time. This represents an approximate maximum computer cost of between $150 and $210 per case. The cost of running TACTICS on an IBM 7094 computer is nearly the same; the running time per case is less but the computer rental cost per unit run time is higher. It is expected that the cost per case on an IBM 360/65 will decrease by a factor of about 1/3, which will change the maximum costs per case to approximately $50 to $70.

SIMULATION

The simulation method, whether it be for training, developing new combat techniques, or R&D design purposes, involves some very complex and specialized equipment and facilities. In the more sophisticated prototypes designed or proposed to date, the major design features include:

1. Two fighter aircraft type cockpits with controls and limited instrumentation
2. A large field of view ("out the window") visual display consisting of target-image and terrain-image generator systems, so displayed and focused that each pilot can visually determine his altitude, his own orientation, and the attitude of the other aircraft.

*A 5 minute engagement was chosen as the length of time for a typical case. The duration of actual close in air-to-air engagements appears to be of this order of magnitude, and a five-minute run is also reasonable for simulation and flight testing. In fact, RAND TACTICS runs generally use only two to five minutes of computer time per case, since the technique used is to examine critical portions of an engagement instead of the entire engagement in one continuous run. Furthermore, it should be noted that the 45 minutes running time is based on a situation wherein the variable step size mode of the TACTICS program is being used and the minimum step size is being used throughout the majority of the run. A running time/flight time ratio of 9 to 1 on the IBM 7044 represents the maximum expected with the TACTICS model.

3. A digital computer complex, possibly supplemented by analogue devices that must accept the control inputs, solve the equation comprising the aircraft model, integrate the appropriate equation of motion, and activate the visual display system accordingly. This requires a number of sophisticated computer programs, and, of course, all computations and display activities must be done in real time. A third-generation computer will probably be required to carry out these computations. The initial cost of such simulations will be high, perhaps on the order of several million dollars per installation. Personnel requirements include analysis and programmer personnel, approximately the same in the case of modeling, with perhaps some added requirements for pilots or pilot-substitutes.
4. In addition, it is generally required that angular rotations (pitch and roll), vibration and noise (for onset of buffet), and g's (g-suite activator) be simulated in a realistic manner.

Since no interconnected two-cockpit fighter aircraft simulator, of the complexity described above has yet been built in its entirety, it is difficult to estimate what the operational cost of such a simulator will be. The Aeronautical Systems Division of the Air Force Systems Command at Wright-Patterson Air Force Base has for sometime been investigating the cost and complexity associated with a simulator for air-to-air combat. The expectation is that runs on the simulator will be relatively cheap compared with actual flight testing. On the other hand, due to the complexity of the simulator (it requires more equipment than just a computer) the cost of running a case will undoubtedly be greater than that for modeling.

FLIGHT TESTING

The flight testing method, when applicable, involves a great deal of expensive equipment, including the aircraft and any necessary modifications plus on-board and/or ground-based instrumentation. Computer facilities for data reduction are likely to be required. Personnel requirements are greater than those for the other methods, since flight crews and aircraft support personnel, including controllers, must be added to the analysts and programmers.

A very rough estimate of costs of a high-quality R&D flight test program can be based on a hypothetical set of equipment and personnel requirements. Assume that a fully instrumented test range is used, that a sizable number of runs are made, and that the modification and flying program uses two two-place fighters over a considerable portion of a year (so that it is reasonable to base aircraft costs on annual operating costs). If two complete flight crews and an alternate pilot are used in the program, and if data reduction requires about 15 minutes per engagement on a second-generation computer, the costs per case, based on 20 minutes of flight time per case can approach $3000.* This is felt to be a reasonable estimate for a program using USAF in-house equipment and facilities.

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*Assumed costs include a test range cost of $3600 per hour and a computer cost of $300 per hour. Airplane and aircrew costs are based on the assumption that 100 runs are made during a 6-month test period. No other personnel costs are included.

IV. MATCHING THE TECHNIQUE TO THE TASK

If for a particular investigation it is apparent that more than one of the three techniques could be used, then an estimate of the total number of modeling runs or simulation runs or test flights, together with cost considerations similar to those discussed above, will allow the investigator to determine, in a rough sense, the relative costs involved in following each of the possible approaches. For most R&D problems, however, one of the methods will clearly be more appropriate to the problem that is being addressed than either of the others, so that a cost comparison may not be meaningful.

Considering the characteristics of the three methods under discussion, it is clear that each has its preferred uses. Computer modeling is most useful for problems related to establishing design criteria--to investigating the theoretical limitations of hardware and techniques and to evaluating the potential utility of proposed systems for which suitable operational tactics can be specified. Simulation is most useful for studying human-factor problems, and problems in which realistic tactics and decisions chosen by a pilot are extremely difficult to specify without having a person in the control loop in real time. Flight tests are most useful for providing checks on the findings of the other methods, verifying hardware performance, and diagnosing problems in hardware.

It may be helpful to consider the rationale for choosing among the methods in the context of some examples. Suppose that the question to be answered is, "What range of aircraft and ordnance system performance capabilities is necessary to insure a successful hit-and-run attack against a specific aircraft using standard air-to-air defensive and offensive tactics?" Flight testing is not the correct approach here because in general existing aircraft cannot successfully accomplish such an attack over a wide range of parameters. In any case, the number of engagements would be large and the measure of effectiveness would be difficult. Simulation would be possible, but since the maneuvers involved in this type of engagement can rather easily be optimized for such aircraft (to some extent depending on the weapon system) there is no need for a pilot in the loop. Modeling could cover a larger variation in parameters at a smaller expense. Therefore, it appears that modeling is the technique best suited for this type of investigation, and that flight testing and simulation are not applicable.

As a corollary example, it is suggested that modeling is generally the appropriate basic technique for investigating design characteristics of guided missiles, since the "tactics" used by the missile are explicitly controlled by their fire control, guidance, and aerodynamic parameters.

If the question is one dominated by human judgment and complex tactics, modeling is probably not the appropriate technique. Suppose that the question is, "Is design A for a fighter aircraft superior to design B for close-in fighting, and to what degree?" The answer will require estimating the outcome of relatively prolonged engagements in which pilot judgment and aircraft handling characteristics are extremely important. The estimates must be based on tactics, and no general system of optimum or preferred fighter tactics yet exists in modeling.* Flight testing is not applicable either, since the question concerns future aircraft, and since a large number of engagements would be required to cover an adequate range of offensive and defensive combinations. The appropriate method here would be simulation. The pilots would supply the tactics by flying the simulated aircraft as they would in a real engagement, and the desired spectrum of combat situations could be covered at much lower cost than in flight test.

Other types of research questions that might be profitably addressed by simulation are those concerned with human factors. For example, the ability of pilots to track targets under g-loading, with the use of helmet-mounted sights, or the ability of pilots to detect targets via visual reconnaissance may be studied with the use of specific types of simulators. These are important applications, but it appears to the authors that the use of manned simulation will in general be subordinate to the use of modeling or flight testing for research and development

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*Modeling can well be used in theoretical studies toward development of optimum tactics, however.

purposes. The chief utility of simulators is likely to remain for some time in the field of training.

If the question is one of technical feasibility, prototype evaluation, diagnosis of problems in a hardware system, or validation of man-machine performance in a fully realistic environment, flight testing is clearly the uniquely applicable method. Modeling or possibly simulation may have been used to determine a weapon system's potential effectiveness, but neither can provide definitive answers for these kinds of questions. To determine the degrading effect of the real world on a weapon system design, one must actually try it out, i.e., flight test a prototype in realistic situations. This suggests that the research and development process should make it easy to perform flight tests of prototypes of the technologically pacing items of proposed new systems. Tests of components, and in some cases, of entire systems, could greatly reduce the uncertainties and hence risks of major new developments. Lead times and costs would generally be smaller, even though the time and cost for a test program may appear to be a serial addition to a development program.

What we are suggesting is that modeling and simulation (and other forms of analysis) have their place, but also their definite limitations in the R&D decisionmaking process. There comes a time when paper analyses must be put aside in favor of experimental and demonstration testing of hardware (here again we find ourselves in strong agreement with Stockfisch). This leads to our final remark on the relationship among these techniques. Each can make its contribution to the other in the course of designing and conducting a research program. To mention only two obvious examples: modeling can be used to define the useful range of parameters to be investigated in the other more cumbersome and costly methods; and flight testing is indispensable as the ultimate check on the validity of methodology and results from the other techniques.

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