A NEW APPROACH FOR ESTABLISHING AERODYNAMIC PERFORMANCE OF FLIGHT TRAINERS

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I. Introduction

The purpose of this paper is to describe the approach taken by the Army on Device 2B31, the CH-47 Helicopter Trainer, to ensure that the aerodynamic performance of the training device satisfactorily duplicates that of the helicopter. To the best of our knowledge, this approach has never been taken before. It is a new concept which acknowledges and addresses an old problem: the lack of documented information defining aerodynamic performance in an accurate, comprehensive fashion.

It has long been recognized in the two areas of performance and flying qualities, in particular, that high fidelity of simulation is critical. Fidelity in these two areas helps assure acceptance of the simulator by the trainee, enables learning of the requisite psychomotor skills, and maximizes the transfer of training.

Despite this recognition by training specialists and despite the attempts of trainer procurement agencies and users to achieve this fidelity, it has not always happened. There are undoubtedly many different reasons why this is so. But there is also one common problem shared by virtually all simulator development programs: definitive data which completely describes the aircraft's handling characteristics under all flying conditions, throughout all flight regimes, is often simply not available. Without this data, the simulator manufacturer cannot properly perform his design function; with it, current technology makes it fully possible to realize the aforementioned fidelity.

Nature of the Problem

In order to understand this problem, it is instructive to briefly review a typical aircraft development program and the evolution of the data which represent the aircraft characteristics. The first step in this process is to configure the aircraft and then develop a mathematical representation of it. This is, in practice, an iterative process.

This mathematical representation takes the form of non-dimensional coefficients whose values are established by the specific airframe/configuration. A total of six basic equations - one for each degree of aircraft freedom - are required to completely define the aircraft motion. It is general practice to develop subequations which define the applied forces and moments. Figure 1 shows one such equation for the forces along the vertical (lift) axis of the aircraft. The terms on the right-hand side of the equation represent the contribution of all of the variables which can effect lift. The coefficients in these terms are, in general, non-linear and have a multi-functional dependency on such aircraft parameters as tip Mach number, angle of attack, sideslip angle, rotor downwash, etc.

The initial attempt at establishing these coefficients is made by the aerodynamicist by referring to the voluminous existing material describing various aerodynamic components, main rotor/rotors, tail rotor, elevator, fuselage, stores, etc. His new airframe is viewed as a collection of these individual aerodynamic components, and he utilizes existing data on these components which are similar to his own. He attempts to correct for the fact that his components may be slightly different in form from those for which data exists and, more importantly, for the fact that this particular combination of aerodynamic components with their resultant interactions, has never before existed. This process makes for obvious inaccuracies, and the coefficient values which result from this process are referred to as "predicted" data. Nevertheless, these data can now be used, in conjunction with equations expressing the aircraft dynamics of motion (normally referred to as the Equations of Motion), to make the initial determination of aircraft performance and flying qualities. By aircraft performance, we mean such characteristics as rate of climb, cruise speeds, and hover power. By flying qualities, we mean such characteristics as longitudinal and lateral stick effectiveness, directional pedal effectiveness, and positive stick gradient.

The accuracy of the predicted coefficients is improved by the next step in the development process: wind tunnel tests. Scaled models of the exact aircraft configuration are installed in wind tunnels and direct measurements of various coefficients are made. These measurements are used to upgrade the coefficients, and more accurate determinations of aircraft performance can be made.

The last step in the design process is flight test. (See Figure 2.) In an ideal flight test program — ideal from the standpoint of the simulator user — a fully-instru-

$$F_{Z_a} = C_{L_{FUS}} A_{REF} q + F_{Z_{SL}} + C_{T_{FR}} (TF) \cos (i_{FR}) + C_{T_{AR}} (TF) \cos (i_{AR}) + F_{Z_{ICE}} + F_{Z_g} \cos \theta + F_{X_g} \sin \theta$$

where:

F	=	Force
Z_a	=	Vertical axis of the aircraft
C	=	Coefficient
L	=	Lift
FUS	=	Fuselage
A_{REF}	=	Reference Area
q	=	Dynamic pressure
SL	=	Sling load
T	=	Thrust
FR	=	Forward rotor
AR	=	Aft rotor
TF	=	Thrust factor
i	=	Incidence angle
ICE	=	Ice accumulation on the fuselage
g	=	Ground reaction forces
θ	=	Pitch attitude

Figure 1. Vertical Force Equation

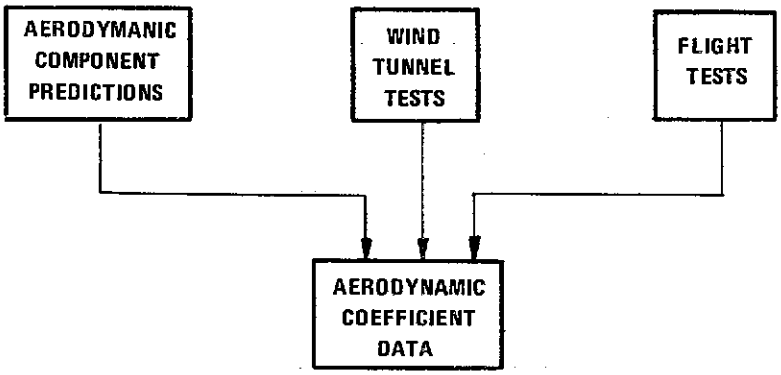

Figure 2. Aerodynamic Data Evolution

mented test aircraft would be flown everywhere in its normal and abnormal flight regimes. Care would be taken to ensure that the full range of flight parameters was explored and precise data gathered for extreme flight conditions and various aircraft configurations. This flight test data would then be reduced, analyzed, and used to further update and refine the coefficient data.

The flight test program is the most crucial step in the process of establishing data for high-fidelity simulator designs. The flight test data could and theoretically should serve as the standard of performance for acceptance of the simulator. The coefficient data derived from the flight test program should serve as the basis of simulator design and permit the mathematical representation of the aircraft — as implemented in the simulator — to duplicate flight test results. Our experience indicates that this ideal situation seldom obtains in practice. Let's look at some of the reasons why it does not.

First of all, developing a precise, accurate mathematical representation of his aircraft is not a primary goal for the airframe manufacturer. He must concern himself with meeting the performance requirements to which he is committed, while ensuring handling qualities that are pilot-acceptable. It is true that in the intermediate process of achieving these goals he utilizes coefficient information, but once into his flight test program, refining the coefficient data extensively and comprehensively becomes something of an academic exercise. It's actual airplane performance — not precise mathematical representation of that performance — that occupies him. Refinement of coefficient data to the level required by high fidelity simulators necessitates an extensive flight test and data analysis program. If his customer is not willing to pay for such a program, the airframe manufacturer can seldom afford to conduct it.

Second, even when a fairly rigorous flight test program has been conducted, it is frequently the case that there are "holes" in the data. In particular, high speed lateral and rearward flight, ground effect on medium and high speed flight, and dutch roll dynamics at high rates of climb are areas where accurate flight test data are normally quite sparse.

Third, the evolutionary process which characterizes many aircraft developments often makes flight test data obsolete. Thus, although the - A version of any aircraft may undergo extensive flight test, the - B, - C, - D, etc. versions may not. This is illustrated in Figure 3, which shows the evolution of the U. S. Army versions of the Huey helicopter. Extensive flight testing was accomplished on the initial configuration, the XH-40, whose production version was designated the UH-1A. But only limited testing was performed thereafter as the fuselage, rotor and engine of the Huey were modified. When the - 13 engine was installed in the UH-1H, which is the version simulated by Device 2B24, the flight testing performed on the new configuration was insignificant.

An extensive instrumented flight test program is currently underway for the Utility Tactical Transport Aircraft System, and thus an excellent base of data will eventually be available for the simulator program. Ten years and six modification programs from now, however, will probably find us facing a similar problem in UTTAS simulations.

Hence, for the reasons just noted, adequate flight test data may not exist at the time that we undertake a simulator development program. And yet it is not the practice to simultaneously undertake a comprehensive flight test program: we expect to make do with existing data.

II. The Traditional Approach

The Army first encountered this problem when it initiated its Synthetic Flight Training Simulator program with the development of the UH-1H simulator: Device 2B24.

We followed what might be called the "traditional" approach to the data problem on this program. The simulator contractor had total responsibility for the acquisition of aerodynamic data. He collected the data that was available — the coefficient data from the aircraft manufacturer — tabulated the data in a Criteria Report, and submitted it for approval to the procurement agency: NTEC/ATDA. The approval which was subsequently granted did not represent an endorsement of the accuracy of the data; it was, instead, an agreement that the data package submitted by the contractor was a complete compilation of all known available data.

The simulator contractor then prepared the Test Procedures and Results Report. This report contains all of the test procedures and standards which will eventually be used in evaluating and accepting the simulator in all areas, but in particular for our purposes here, in the performance and flying qualities areas. It is developed by utilizing the coefficient data from the Criteria Report in off-line computer programs to compute performance and flying qualities. Since these off-line programs are not required to run in real-time on the simulator, they need not employ the economies that the real-time simulator computers/

MODEL	DESIGNATION	FUSELAGE LENGTH	ROTOR DIAMETER	ENGINE	FLIGHT TEST
204	UH-1A	38 FT.	44 FT.	T-53-L-1A	Extensive Testing (XH-40)
	UH-1B	38 FT.	44 FT.	T-53-L-5 T-53-L-9 T-53-L-11	Stability and Control Tests
	UH-1C	38 FT.	44 FT.	T-53-L-11	Limited Testing
	UH-1M	38 FT.	44 FT.	T-53-L-13	None
205	UH-1D	42 FT.	48 FT.	T-53-L-11	Limited Testing
	UH-1H	42 FT.	48 FT.	T-53-L-13	None

Figure 3. Huey Evolution

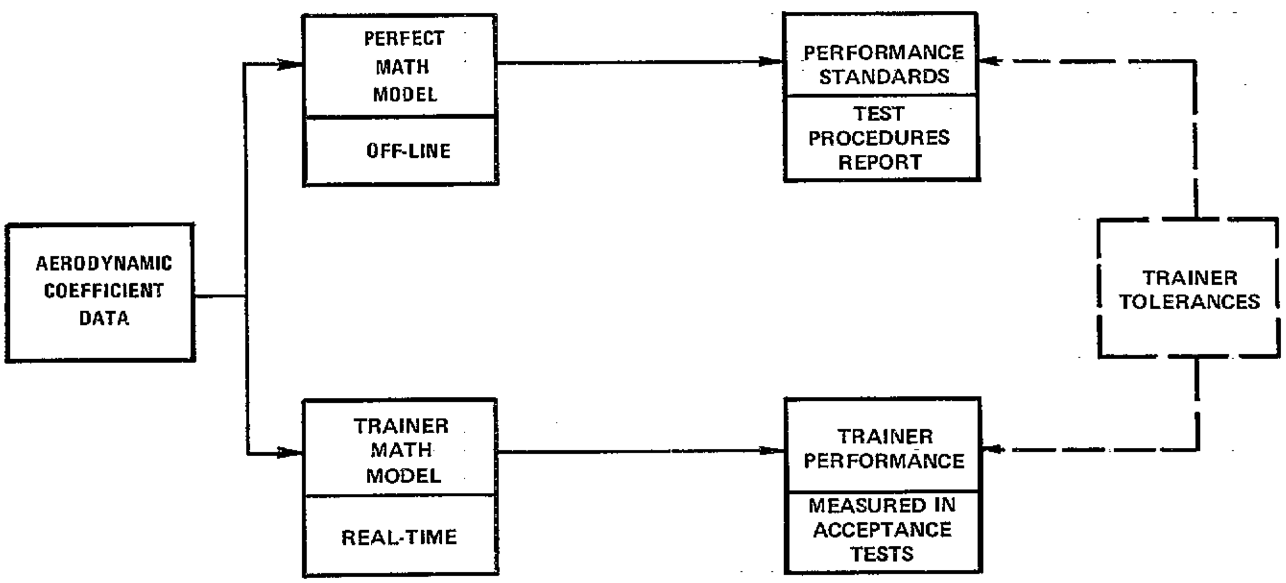

Figure 4. Acceptance Test Procedures

programs do. (These economies include considerations of coefficient data representation, iteration rates, integration techniques, word length, and equation complexity.) These off-line programs thus represent near-perfect math models which introduce negligible errors into the computation of performance and flying qualities.

The Test Procedures and Results Report was also submitted for approval by the contracting agency. Again, approval of this report did not represent user-pilot concurrence with the accuracy of the report's contents; it was an agreement that the test specified covered each paragraph in the trainer specification to assure that the simulator complied with the specification.

In parallel with this effort the simulator design activities continued. It is important to understand the concept of simulator tolerances in the context of the design activities. Tolerances on the values and curves depicting performance and flying qualities are included in every simulator contract. In the case of Device 2B24, the tolerances were specified in the trainer specification. The goal of the simulator designer is to match the performance specified by the Test Procedures and Results Report within the tolerances specified by the trainer specification.

These relationships are shown in Figure 4. Notice that the measured trainer performance is not being compared against flight test data, but against standards in a Test Procedures Report which have been based on the available coefficient data. If the coefficient data is accurate and complete, this is a satisfactory approach and the simulator will fly like the aircraft. If not, the simulator will not fly like the aircraft.

In accordance with this procedure, it was not until the start of In-Plant Preliminary Inspection that Army pilots had their first opportunity to judge how well the trainer flew. The pilot evaluations during this inspection period uncovered numerous discrepancies between simulator and aircraft performance. These discrepancies included rotor control gearing simulation, break-out forces, slip indicator sensitivity, torque pressure, and several other areas which affected simulator fidelity.

Immediate fixes during inspection were possible in the case of some of the discrepancies; others, which required more time for correction, could not be properly addressed during the inspection period because of trainer need dates and contractual considerations.

Virtually all of these performance and flying qualities discrepancies have been — over a period of time — corrected in Device 2B24. But, it was clear, in retrospect, that the simulator acceptance period was not the proper time to uncover discrepancies of this nature. A better procedure was required, one which realistically addressed the data problem.

III. The Device 2B31 Approach

I would now like to describe what we believe to be a greatly improved procedure: the one being used on Device 2B31, the CH-47 simulator. We elected to use this procedure because of concern about the adequacy of the available coefficient data. We will return to this issue shortly.

In the 2B31 procedure, the simulator contractor still had the initial responsibility for the acquisition of aerodynamic data. He still collected this data and incorporated it in the Criteria Report, which was submitted to the Government for approval. He still proceeded with simulator design based on the data in the Criteria Report. But here our new procedure departed from the old in four important respects.

First, the Army established a pilot evaluation team to provide preliminary evaluations of the trainer prior to the start of formal acceptance testing. These preliminary evaluations were conducted in several phases, with each phase utilizing the same designated team leader and a different assistant pilot.

Each phase was a joint, constructive work session. The participants were the two Army pilots, the NTEC Project Engineer, and the contractor design engineers. In the first phase, gross flight handling and steady-state performance discrepancies were noted by the pilots. Discrepancy Reports (DR's) were written and worked out by the participants. Many discrepancies were corrected during this first visit; others were left to be corrected in time for evaluation at the second session. Correction of the discrepancies required extensive modification of the coefficient data originally supplied to the simulator contractor.

The second and third sessions were quite similar. Old DR's were re-evaluated; new DR's were written; both old and new DR's were jointly worked on, corrected, and approved. By the end of the second session the simulator was flying very much like the aircraft and the team's efforts were starting to concentrate on the more subtle aspects of handling qualities. By the end of the third session, the pilots were unable to identify any significant discrepancies between the simulator and the aircraft performance and flying qualities.

Device 2B31 includes a camera-model visual system, and the first three evaluation sessions were conducted prior to its integration with the flight simulator. Since it is well established that the presence of a visual system magnifies any deviations in simulator performance from that of the aircraft, two additional sessions are scheduled after visual integration. Visual integration will occur subsequent to the publication of this paper.

The second departure from the older procedure has to do with flight time for Contractor engineering personnel. At the beginning of the program, Contractor personnel went along on a routine CH-47 training flight for orientation purposes. The trip included discussions between Army instructor pilots and Contractor personnel about aircraft flying qualities, pilot technique, etc.

After the first evaluation session described earlier, the evaluation pilots requested that Contractor personnel get more flight time in the CH-47. The pilots felt that verbal descriptions were not adequate, and that the designers needed to experience the more subtle characteristics of aircraft handling qualities. This request resulted in several additional Contractor test flights, in which contractor personnel observed pilot actions, as well as aircraft performance and instrument indications. Each test flight revealed new, useful information which was subsequently incorporated in the trainer. All of the program participants felt this flight time to be invaluable.

The third departure from the older procedure is related to the Test Procedures and Results Report. This report, as indicated earlier, has normally been based on original coefficient data. This same procedure was followed initially on the 2B31 program, except that the quantity of test conditions was kept relatively small. This limited test procedure was then used by the contractor for internal test purposes prior to the first evaluation phase. The purpose of the evaluation team was to make the simulator performance match aircraft performance; a purpose which was achieved, as it turned out, only after extensive modifications were made to simulator performance. Changes in simulator performance could only be achieved by modifying the original coefficient data stored in the simulator computer. That is, the tailoring process instigated by the evaluation team dictated changes in simulator performance which required changes at the aerodynamic coefficient level. The resulting coefficients differed substantially from those originally supplied to, and utilized by, the simulator contractor.

Under these circumstances it is obvious that a Test Procedures Report based on the original coefficients had no meaning, and that computation of extensive performance standards based on the "perfect" math model became a useless exercise. In our new procedure, therefore, the results of the evaluation phases — as measured on the simulator — were incorporated into the appropriate sections of the Test Procedures Report, since those results represented our best determination of performance and flying qualities.

The fourth and final departure from the older procedure concerns tolerances. This consideration is related to the one involving the Test Procedures Report. As we mentioned earlier, tolerances have normally been construed as limits established with respect to standards in the Test Procedures Report which the simulator must not exceed. But when the Test Procedures Report was itself derived from the simulator — as noted in the previous paragraph — this interpretation of tolerances needs to be reconsidered. Tolerances in this new procedure are still considered to be limits relative to Test Procedure Standards. But they are now used to verify that (a) the simulator's performance has not changed (as a function of time, other simulator modifications, etc.) and (b) that any follow-on simulator performs like its predecessors.

The 2B31 design was originally based on coefficient data supplied by the aircraft manufacturer, supplemented by data developed by the simulator manufacturer in areas of missing data. Using this data base, the simulator was flyable initially but only marginally stable. Pilot evaluations were then used to systematically change simulator performance in both steady-state performance and handling qualities. These changes included:

1. Longitudinal and directional sensitivity.

2. Angle of attack and speed stability as well as positive stick gradient.

3. Trim longitudinal stick position as a function of airspeed.

4. Adjustments to match Operations Manual hover, speed, and climb performance.

5. Coordinated turns with lateral stick only. (No directional pedals required.)

6. Two-wheel taxi capability with proper control application.

7. Autorotational flying qualities.

8. Acceleration and deceleration characteristics.

9. Hovering control characteristics.

10. Secondary effects of changes in collective pitch on speed and changes in differential.

11. Collective pitch on rate of climb.

As this paper is being prepared, the three phases of evaluation which precede visual integration have been completed. Some flight problems still exist, but the lead evaluation pilot feels that "only an expert could tell the difference between the simulator and the aircraft". In view of this condition, additional refinements will be postponed until after visual integration has been completed. The simulator contractor has commented that the information provided by the evaluation team has been vital to the development program. The increase in in-plant test time which has been the inevitable result of the evaluation phases, is acknowledged by all program participants to have been a worthwhile investment from the standpoint of increased fidelity, and hence reduced acceptance time.

IV. Conclusion

In summary, we would like to make the following points:

1. The data available from the aircraft program quantitatively describing the aircraft characteristics is frequently inadequate to support the design and acceptance of the high fidelity simulators which we require in the '70's. This statement is not intended to imply that all such data is inadequate, for that is not the case. Nor is it intended as criticism of the aircraft programs or aircraft manufacturers. As noted earlier in this paper, there are differences in the accuracy and explicitness of the data required by the aircraft manufacturer and the simulator manufacturer. These differences make it unrealistic to expect that the available data will prove totally adequate.

2. Two basic approaches can be taken to solve this problem of additional data needed for a simulator development program. First, an aircraft can be instrumented, flown extensively, and the resulting flight test data reduced and analyzed to provide an accurate update of the aerodynamic coefficient data. This is an expensive, time-consuming process which is best included in the original aircraft development program. The second approach is to utilize the knowledge of experienced, qualified personnel — supplemented by flight time — to match aircraft and simulator characteristics. The latter approach was taken on the 2B31 program by creating an evaluation team comprised of user pilots.

3. Two questions which had to be answered in setting up the Test/Evaluation team were: How many separate sessions on the simulator would the evaluation team require and what complement of people should participate? Three phases were selected for the period prior to and two phases will be implemented subsequent to visual integration. Experience to date indicates three phases prior to visual integration to be optimum. Two team members attended each phase. One of the team — the team leader — participated in each phase to ensure consistency from phase to phase. The other team member was different each time in order to provide fresh inputs and to avoid simulator characteristics rather than enforcing the aircraft characteristics from the simulator.

4. It is implicit in this approach that evaluation team comments and changes take precedence over other data sources. The approach acknowledges that information from these experts is the best data available. The contractual implication of this position is that the evaluation team has the authority to change the data used by the Contractor in the design of the simulator. Thus, if large quantities of ECP's are to be avoided, the contract must include provisions to cover these changes and the various engineering documents must be modified to incorporate them.

5. In particular, the Test Procedures Report takes on a different significance in this situation. Originally, this report contained performance standards which were computed from design data. In the 2B31 these performance standards were established by the evaluation team. Hence, the Test Procedures Report was created by measuring and recording simulator performance after the evaluation team had determined that the simulator performance duplicated the CH-47. Thus the Test Procedures Report contained measured results rather than calculated standards.

The need for more simulator time by military personnel has been accompanied by demands for levels of fidelity in the simulator which require its characteristics to be virtually indistinguishable from those of the aircraft itself. In the Device 2B31 program we have achieved this fidelity through a co-operative effort involving experienced using command pilots, procurement agency engineers, and contractor design personnel. We anticipate that many of the techniques and innovations which have been devised and employed on this program will become standard procedures in future Army simulator procurements.

ABOUT THE AUTHOR

MAJOR (P) ROBERT L. CATRON is assigned to the U.S. Army Training Device Agency as Project Director for the Army's Synthetic Flight Training System (SFTS). He holds a B.S. degree and is currently completing requirements for an M.B.A. degree. He is also a graduate of the Command and General Staff College and University of Southern California's Aerospace Safety Management Program. Major Catron has been associated with the flight simulation program for the past 3 years. He has had numerous articles published on simulation and has made presentations on the subject to several military and civilian agencies.