AUTOMATED FLIGHT TEST DATA CORRELATOR FOR A HELICOPTER FLIGHT TRAINING SIMULATOR

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ABSTRACT

This paper discusses an accurate, semi-automated method for increasing the performance fidelity of a helicopter flight training system's aerodynamic model. The method employs an automated correlation algorithm known as AUTOCOR for systematic adjustments of the quasi-static mathematical model using fundamental aerodynamic model parameters. The AUTOCOR algorithm is divided into two phases. The first concerns calculation of the incremental forces and moments necessary to modify the vehicle's static trim attitudes and pilot control positions to match those of the actual helicopter throughout its entire flight maneuver envelope. The second phase centers on optimal incorporation of these forces, moments, and other empirical adjustments into the simulator's model data tables by judicious use of numerical techniques. The AUTOCOR algorithm provides satisfactory results even with an incomplete flight test data set.

INTRODUCTION

There is no question of the importance of aerodynamic fidelity for the successful simulation of a full-mission helicopter. Correct aircraft flying qualities, both static and dynamic, are a fundamental training systems building block. The level of acceptable fidelity for military helicopter simulators has, in the past, been judged largely by pilot evaluation and tailoring. However, pilot tailoring of simulator math models is imprecise by its nature and thus a potentially time-intensive and unbounded task.

Recognizing this, increased emphasis on matching extensive aircraft static and dynamic flight test data (FTD) shows a potential for eliminating subjective tailoring for Army helicopters, much as many commercial aircraft simulators are developed today.

The current development of the Singer-Link Black Hawk full-mission simulator represents a program which reflects the continuing trend towards FTD correlation of the simulator. This simulation program has a requirement for matching an extensive FTD set (greater than 2,000 points), while still including pilot evaluation in regions where flight test data is unavailable. As shown in Table 1, this data covers the flight envelope of airspeed from -45 to +160 knots, density altitude from sea level to 15,000 feet, and gross weight from 15,100 to 22,000 lbs (external stores support system configuration).

FLIGHT TEST	ALTITUDE RANGE (ft)		SPEED RANGE (knots)	
STATIC LONGITUDINAL STABILITY	2,000 TO	10,000	88 TO	152
STATIC LATERAL STABILITY	2,000	10,000	55	124
CONTROLLABILITY - ALL AXES	2,400	6,800	45	140
MANEUVERING STABILITY	3,500	11,000	100	132
DYNAMIC STABILITY - ALL AXES	2,000	7,300	0	100
LEVEL FLIGHT PERFORMANCE	2,600	14,000	40	160
CONTROL TRIMS	400	10,000	-45	155
			±45 KNOTS SIDE FLIGHT	
HOVER PERFORMANCE (IGE AND OGE)	2,100	12,000		
CLIMB PERFORMANCE	0	15,000	0	83
AUTOROTATION ROD VS AIRSPEED	5,000	6,000	40	130
ROD VS MAIN ROTOR RPM	5,000	6,000	40	130

IGE = IN GROUND EFFECT
OGE = OUT OF GROUND EFFECT

TABLE 1 BLACK HAWK FLIGHT TEST DATA (FTD)

The AUTOCOR computer program was developed in response to these expanded requirements. This two-phase interactive program assists in identifying aerodynamic model deficiencies and in making the necessary analytic and empirical corrections to the model.

The fundamental principles of this technique are documented, with examples, by Hazen(1). In brief, Hazen iterated upon incremental net vehicle forces and moments until the desired static aircraft attitude and control positions were obtained. These adjustments were then manually incorporated into the aircraft aerodynamic model as a smooth function of appropriate variables. For example, one might match desired fuselage pitch attitude by introducing an empirical pitching moment about the center of gravity as a function of airspeed. These forces and moments are illustrated in Figure 1. The AUTOCOR program expands this general approach by adding flexibility to sources of the necessary force and moment increments, and mechanization to the process of modifying the model data that characterizes these needed increments.

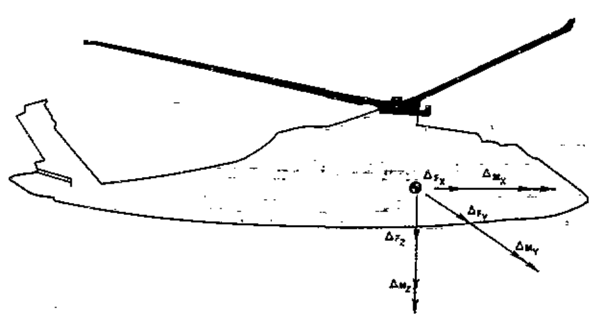


FIGURE 1 HAZEN-TYPE INCREMENTAL GENERAL FORCES AND MOMENTS ABOUT THE AIRCRAFT CENTER OF GRAVITY

STATEMENT OF PROBLEM

The helicopter dynamical flight model is highly nonlinear in comparison to a fixed-wing aircraft model. The inability to rely heavily on constant coefficient modeling techniques within the helicopter flight math model results in a complex representation of the aerodynamic characteristics of the helicopter. This math model complexity is further aggravated by the wide range of unsteady flight regimes in which the helicopter operates. This makes it necessary to model the effects of unsteady flow fields within the math model of the real-time, full-mission helicopter training simulator.

Force and moment coefficients within the helicopter math model change extensively across the flight regime of the helicopter; therefore they are best represented in tabular or data map form. Table 2 lists some of the coefficient tables used in the Black Hawk simulation. Baseline values of such coefficients are calculated by analytic prediction or come from some empirical source (e.g., wind tunnel tests). However, because of the nonlinear and unsteady effects, each flight regime of the helicopter (see Table 1) subjects the baseline coefficients to extensive modifications in order to better predict the true flight characteristics of the helicopter. These necessary modifications differentiate the training simulator math modeling task from the engineering research and development aerodynamic math modeling task.

TABLE NAME		INDEPENDENT VARIABLES
C_H	MAIN ROTOR DRAG FORCE	$(\lambda_0, \mu_0, \theta_{MR})$
C_Y	MAIN ROTOR SIDE FORCE	$(\lambda_0, \mu_0, \theta_{MR})$
C_T	MAIN ROTOR THRUST FORCE	$(\lambda_0, \mu_0, \theta_{MR})$
C_Q	MAIN ROTOR TORQUE	$(\lambda_0, \mu_0, \theta_{MR})$
$C_{T_{TR}}$	TAIL ROTOR THRUST	$(\lambda_{0_{TR}}, \mu_{0_{TR}}, \theta_{TR})$
$C_{Q_{TR}}$	TAIL ROTOR TORQUE	$(\lambda_{0_{TR}}, \mu_{0_{TR}}, \theta_{TR})$
L_{HT}	HORIZONTAL TAIL LIFT	(α_{HT})
D_{HT}	HORIZONTAL TAIL DRAG	(α_{HT})
L_{VT}	VERTICAL TAIL LIFT	(β_{VT})
D_{VT}	VERTICAL TAIL DRAG	(β_{VT})
$M_{X_{FUS}}$	FUSELAGE X-MOMENT	(β_{FUS})
$M_{Y_{FUS}}$	FUSELAGE Y-MOMENT	$(\alpha_{FUS}, \beta_{FUS})$
$M_{Z_{FUS}}$	FUSELAGE Z-MOMENT	(β_{FUS})
L_{FUS}	FUSELAGE LIFT	$(\alpha_{FUS}, \beta_{FUS})$
D_{FUS}	FUSELAGE DRAG	$(\alpha_{FUS}, \beta_{FUS})$
Y_{FUS}	FUSELAGE SIDE FORCE	$(\alpha_{FUS}, \beta_{FUS})$

α = angle of attack
β = angle of sideslip
μ_0 = advance ratio
λ_0 = inflow ratio
θ = collective pitch of the rotor blades

TABLE 2 BLACK HAWK AEROMODEL COEFFICIENT TABLE

Understandably, manual manipulation of these data tables to satisfy a static flight test data point is a tedious process at best. Automating this process as much as possible becomes a necessity.

The AUTOCOR technique is valid with any simulation model or portion of that model. The desired forces and moments to be modified need not preexist as coefficients in tabular form within the simulation model. For example, the rotor thrust determined by a blade element rotor model is analytically calculated from C_l and C_d data for the individual rotor blades. The engineer could use AUTOCOR either to modify the C_l and C_d tables or, more directly, to create a supplementary table of additional main rotor thrust values necessary to satisfy a series of static FTD points. The following discussion uses "level flight control trims" as a specific example. The techniques discussed are, of course, more widely applicable.

FORMULATION OF SOLUTION

AUTOCOR is divided into two phases or steps. Phase One allows the engineer to choose and systematically solve for coefficient table changes necessary to meet flight test data. The program outputs "delta" files containing the requested modifications in terms of increments to model coefficients. Phase Two of the AUTOCOR program incorporates these modifications back into the baseline model coefficient tables, smoothing the necessary changes in the original data set.

Phase One: Determination of Deltas

A "complete" data set for a static level flight condition consists of pilot control positions and aircraft attitudes as well as shaft horsepower, as shown in Table 3. The engineer selects the coefficients to be modified by AUTOCOR until the FTD case is matched. A typical level flight control position test set is shown in Figure 4. Table 3 lists an example of an engineering estimate of which coefficient tables might be responsible for the model's failure to match FTD for this test set. This solution is unique: the assignments could be rearranged within the table, possibly resulting in a slower convergence, but the answer would be the same. Allowing the engineer to choose which coefficient is suspect is a modification of the system described by Hazen.[1] All modeling errors were previously attributed to general forces and moments applied at the center of gravity. The predominance of main rotor force and moment contributions in the example is indicative of the main rotor's powerful influence on the entire aircraft trim condition.

FLIGHT TEST DATA VALUE: (FIGURE 2, 90 KNOTS)		"BEST GUESS" COEFFICIENT TABLE TO BE MODIFIED:	HAZEN "BEST GUESS" ASSIGNMENTS:
θ_b	PITCH ATTITUDE	$C_{H_{MR}}$	M_Y
ϕ	ROLL ATTITUDE	$C_{Y_{MR}}$	M_X
δ_a	LATERAL CYCLIC	LATERAL FLAPPING (b_1)	F_Y
δ_b	LONGITUDINAL CYCLIC	LONGITUDINAL FLAPPING (a_1)	F_X
δ_c	COLLECTIVE CONTROL	$C_{T_{MR}}$	F_Z
δ_d	DIRECTIONAL CONTROL	$C_{T_{TR}}$	M_Z
SHP	SHAFT HORSEPOWER	$C_{Q_{MR}}$	-

TABLE 3 ENGINEERING "BEST GUESS" FOR CORRELATION LOOP ASSIGNMENTS FOR BOTH CURRENT ALGORITHM AND HAZEN-TYPE ALGORITHM

FLIGHT TEST DATA VALUE: (FIGURE 2, 90 KNOTS)	CORRELATED TRIMMER RESULT:	BASELINE COEFFICIENT TABLE VALUE:	MODIFICATION TO TABLE NECESSARY TO MATCH FTD:
θ_b = -0.4688 DEGREES	0.4669	$C_{H_{MR}}$ = 0.00080	$C_{H_{MR}}$ = 0.00019
ϕ = SET TO 0.0	0.0000	$C_{Y_{MR}}$ = 0.00002	$C_{Y_{MR}}$ = 0.00000
δ_a = 51.1192 PERCENT	51.1641	b_1 = -0.55 DEGREES	b_1 = -0.48
δ_b = 41.0766 PERCENT	41.4039	a_1 = 1.69 DEGREES	a_1 = 1.72
δ_c = 46.7776 PERCENT	46.7931	$C_{T_{MR}}$ = 0.0071	$C_{T_{MR}}$ = 0.00024
δ_d = 50.8379 PERCENT	50.8361	$C_{T_{TR}}$ = 0.0100	$C_{T_{TR}}$ = -0.00234
SHP = NOT AVAILABLE	1182.04 HP	$C_{Q_{MR}}$ = 0.00034	$C_{Q_{MR}}$ = NOT CALCULATED

TABLE 4 EXAMPLE COEFFICIENT MODIFICATION FOR A 90-KNOT LEVEL FLIGHT CONTROL TRIM POINT CORRESPONDING TO THE FLIGHT TEST DATA OF FIGURE 4

For the Black Hawk, original main rotor and tilt rotor coefficient data were computed off line, in non-real time, by the airframe manufacturer's preferred rotor analysis models. Thus the baseline table for static conditions represents the most accurate analytic model available.

Phase One is constructed of trimmer and correlator programs, usually running simultaneously.

__Trimmer.__ The trimmer program is a trimming algorithm that iterates aircraft orientations and pilot control positions to obtain a zero-acceleration condition (much the same as a pilot in the loop would). It must also maintain specified airspeed, altitude, and sideslip angle for level flight. Trimming algorithms are available for all of the "standard" types of flight conditions corresponding to the flight tests listed in Table 1. The FTD correlation is successful when the resulting pilot control positions and attitudes computed by the trimmer match those of the FTD.

__Correlator.__ The correlator is an extension of the aircraft trimmer concept, since they both drive the accelerations to zero. However, pilot control positions and aircraft attitude are also specified. The modeled vehicle forces and moments are modified (through the specified coefficients) to provide the desired unique solution shown as an example in Table 4. In order to run the isolated (i.e., no trimmer) correlation algorithm, the engineer must either have a *full set of FTD* — $\theta_b, \phi, \delta_a, \delta_b, \delta_c, \delta_d$, *Shaft* Horsepower — or a "best guess" for any missing data.

__Problem of Missing Data.__ Usually, FTD reports do not contain complete data sets for most test cases. In Figure 4, for example, roll attitude and shaft horsepower are missing. Occasionally, incomplete individual FTD cases can be combined to create a more complete data set. This is the case, most often, for control trims and level flight performance. A framework across gross weight and altitude, using these instances of relatively complete data points, provides the engineer with a gauge to judge the accuracy of coefficient table modifications made by less completely defined points.

The second, more frequently used approach is to estimate values of the missing data. This requires extrapolation from similar but more complete data, a best guess, or the advice of an experienced test pilot. Another method of supplying the missing data is to derive these data by the trimmer algorithm. This method, in the case of very sparse data (e.g., rate of climb as a function of shaft horsepower and airspeed), can create apparent data discrepancies in the maps. This happens when the trimmer provides control positions and aircraft attitudes significantly different from those of the aircraft. In effect it creates a bad data point for the correlator to match.

Once the correlator has converged on a stable solution, a record of the trim is made. This record contains the values of the independent variables for each modified coefficient. Also contained in this record is the baseline coefficient (the value interpolated from the original table) and the increment the correlator was forced to add to trim the aircraft. This record is gathered with similar records from other tests to form a "delta" file. This file forms the principal input to Phase Two of the AUTOCOR program.

__Phase Two: Incorporation of the Function Modifications__

Phase Two of the AUTOCOR program is responsible for modifying the baseline coefficient tables using the "delta" file from the correlator. Three numerical techniques form the backbone of this program. The remainder of the program deals with file input/output, plotting, and various other ancillary functions.

Before discussing implementation of AUTOCOR, a brief survey of the mathematical problem of incorporating deltas back into the baseline tables is helpful. As shown in Figure 2, the most

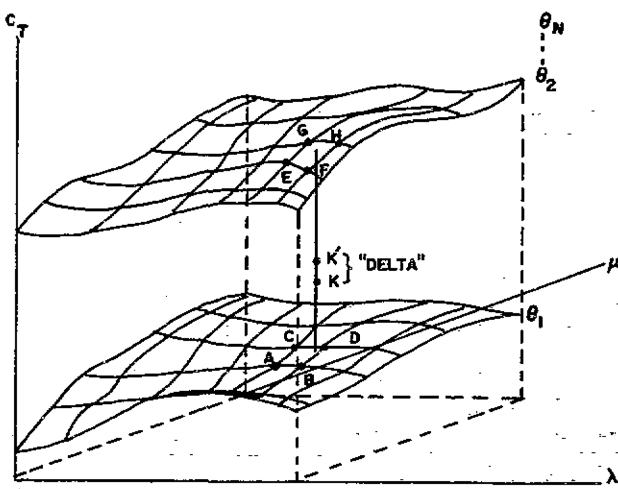


FIGURE 2 TWO SURFACES OF THE TRIVARIATE FUNCTION $C_T(\lambda_o, \mu_o, \theta)$

general case for the Black Hawk simulator math model is a function of three variables. For example, C_T of the main rotor is represented by "stacked sheets," each of which is a lattice of discrete, unequally spaced function values at particular values of the independent variables λ_o, μ_o, and θ. The functional value indicated by point "K" can be obtained by linearly interpolating among the immediately surrounding points "A" through "H." The Phase One correlator determines a "delta" such that the new required value is "K'." The problem is then how to modify points "A" through "H" so that a linear interpolation between the new points will yield "K'." The problem is complicated by the fact that more data points in addition to "K'" may be within the region defined by "A" through "H." There are also many adjacent regions making up the total functional envelope defined in Figure 2 which may also contain deltas. Phase Two of AUTOCOR addresses these problems. An overview of its numerical techniques and implementation follows.

<u>Numerical Techniques for "Delta" Incorporation.</u> The function tables are discrete, with unequal spacing of independent variable coordinates, or "breakpoints." The three techniques currently in use are simple averaging, slope ratio averaging, and linear regression. The first method, simple averaging, takes an arithmetic average of all the deltas that affect a given breakpoint. In Figure 3, the four deltas x_4, x_5, x_6, and x_7 all affect the modification of the coefficient at the breakpoint βFUS_7. The average of the four points is applied to the breakpoint. This method is then applied to each breakpoint that has a delta (or deltas) adjacent to it.

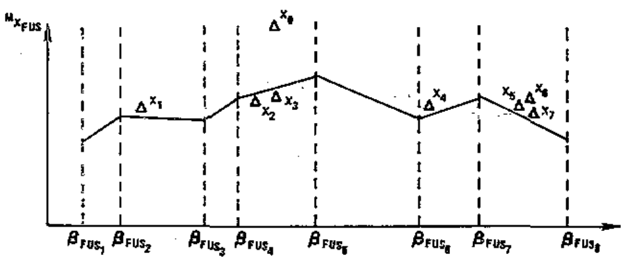


FIGURE 3 TYPICAL MONOVARIATE FUNCTION

The slope ratio averaging technique is quite similar except that a weighting feature is included. The amount a delta can affect a breakpoint is proportional to its proximity to that breakpoint. A delta very close to a breakpoint would be weighted more heavily than a delta farther away (such as x_4 in relation to βFUS_7).

The last method uses linear regression to modify the table. A least-squares criterion minimizes residual errors when fitting a line to the original table points and the delta points. The regression line is passed through the data table along each of its axes. In the case of a trivariate table, three regression lines are drawn through each breakpoint. The average of the three is used as the final value at that breakpoint. Flight test data tends to create isolated clumps of deltas, regions of the coefficient maps where many test points fall, separated by large areas of no experimental data. Frequently, several deltas fall between adjacent breakpoints as a result of this clumping of data. The engineer must choose a numerical method best suited to the available data.

Each of these techniques has its limitations and strengths. Simple averaging is very useful if there is a low level of confidence in the original baseline table. Simple averaging can, in one pass, restructure a table. This technique would be useful for the initial creation of a table. For example, since lateral flapping is calculated by an analytic expression in the Black Hawk math model, a coefficient table was created to house the delta corrections in lateral flapping necessary to fine-tune lateral control position. Its strengths are also its limitations. It is poor for fine-tuning a table because averaging can change the breakpoint values by large amounts in a single pass.

Slope ratio averaging is useful for restructuring a new map while using the delta information to improve the slopes. However, like simple averaging, it is not useful for fine-tuning the maps.

Linear regression is the preferred method during the later stages of map manipulation. It maintains a more continuous slope and filters out large changes. For this reason it may take several correlator passes to match FTD.

<u>Curve Smoothing Techniques.</u> Frequently delta incorporation by the methods just described yields "spikes" or rough spots which can lead to dynamic oscillations as the model passes through static solutions. In Figure 3, x_0 represents a delta point which would likely create a spike in the otherwise smooth function curve. To remedy this problem (which is caused by insufficient and inconsistent data) a curve smoothing technique is desirable. AUTOCOR provides three curve fitting methods: polynominal curve fit smoothing, linear regression smoothing, and modified data smoothing.

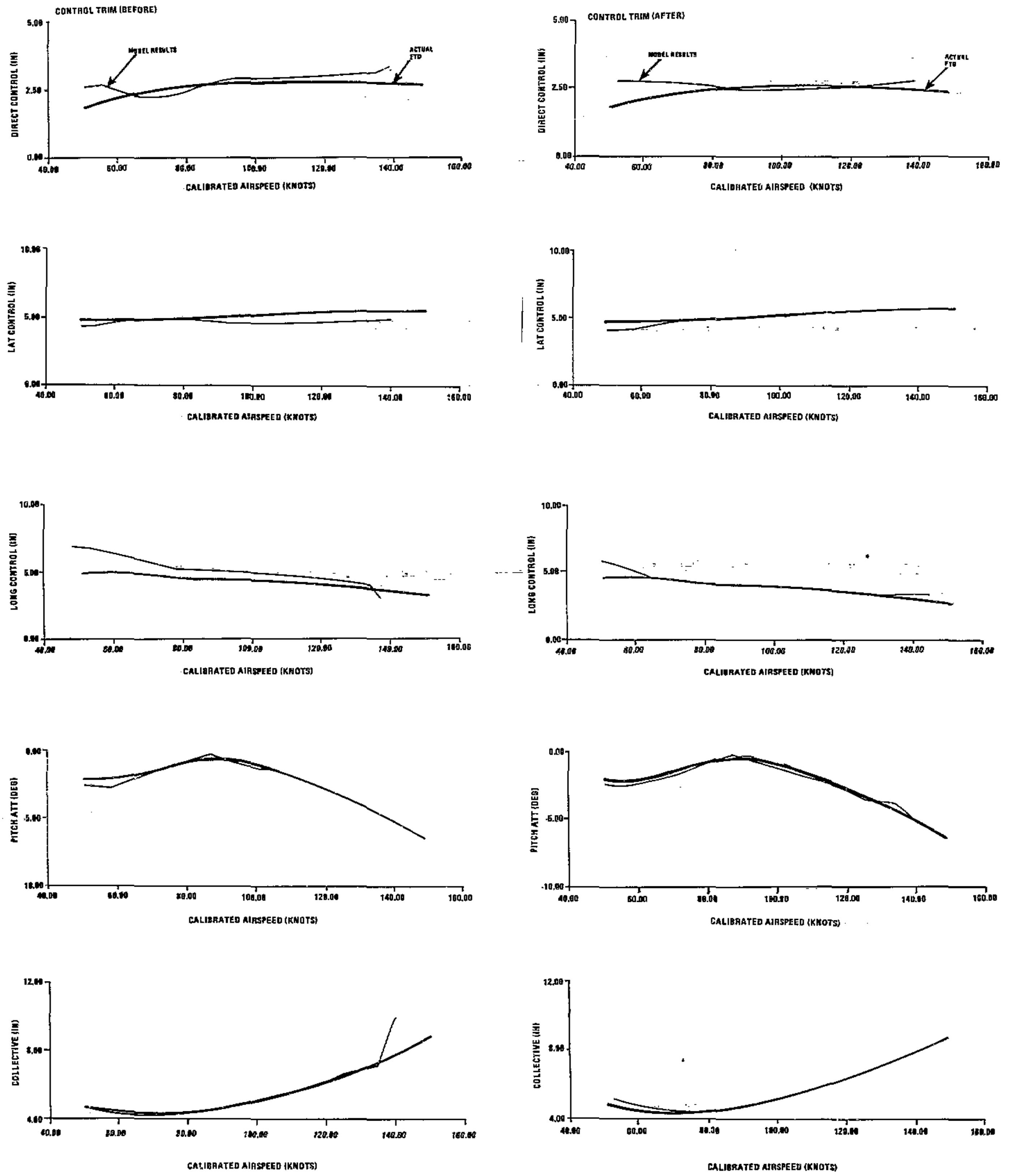
The polynomial fit smoothes the entire data table. Thus a single "spike" may have a powerful influence on the entire map. This method is seldom used because the resulting curve shapes frequently depart too far from the baseline data.

The linear regression method is more localized about the region of the "spike." It is the preferred method for repeated overall smoothing of the maps because it gradually removes spikes without drastically distorting overall map shape. This method fits a line based on a least-squares criterion through successive sets of three breakpoint function values and then averages the computed values at each breakpoint.

The modified data smoothing method allows the number of adjacent breakpoints included in each regression to be specified. This method also has the characteristic that only breakpoints modified by deltas are affected. This allows, for example, linear regression on cruise condition points without changing a satisfactory slow speed regime.

The improvement in model fidelity possible after a single pass through AUTOCOR is shown in Figure 4. In this example full linear regression smoothing of the maps was used to incorporate the delta points. Repeated passes through the AUTOCOR algorithm would further improve data matching in the low-speed regime.

<u>Implementation of AUTOCOR Task.</u> The user begins by loading the numerical values of the baseline data tables from the simulator model into AUTOCOR. Both function and independent variable values can be readily obtained from these files. The user then runs the correlation. The user has sub-options to correlate one or all of the coefficient functions and, after execution, can rerun the analysis using a new (or the same) function as well as a new (or the same) method. The option to smooth the computed function curves to reduce the effects of peaks resulting from erroneous data is always available. During or after cycles of correlation and smoothing, the user may choose 2-D or 3-D (perspective) plots of any function. Cross plots for independent variables are also available. AUTOCOR outputs the tables in a form immediately usable by the simulator models.



(a) BEFORE (b) AFTER

FIGURE 4 MODEL RESULTS BEFORE AND AFTER AUTOCOR ADJUSTMENT

RESULTS AND CONCLUSIONS

The AUTOCOR program represents a first attempt to fully automate the flight test data correlation task within the development of a training simulator. Table 4 is an example of the typically excellent performance of the AUTOCOR algorithm on an isolated flight test data point. This level of accuracy can usually be maintained within a flight test sweep (Figure 4). However, combining individual test sweeps (i.e., over the airspeed range +50 to +150 knots) creates a more challenging task. Major conclusions regarding the performance of the AUTOCOR techniques, as demonstrated during the Black Hawk project, are:

1) Current application of AUTOCOR is limited in part by the type of flight test data available. Flight test data must be self-consistent and complete or conflicts will arise within the coefficient maps.

2) As a result of (1), AUTOCOR is best applied in a series of small steps (for example, one type of flight test at a time, or even one test case at a time) so that only small regions of the maps are altered. Conflicts between correlation runs must be carefully studied and resolved.

3) The most efficient uses of AUTOCOR techniques are methods which allow the engineer to be interactive with the process, particularly with respect to selecting automated options and monitoring results between AUTOCOR steps. This must be done in order to select the best option for any succeeding step in the process.

4) The AUTOCOR concept was applied for the first time to a helicopter training simulator development project (Black Hawk). The conclusion from this initial application is that further development of AUTOCOR can yield an effective, powerful design tool for future use.

RECOMMENDATIONS

1) Pilot-in-the-loop testing of the simulator must be performed parallel to the FTD correlation effort. Modifications to the coefficient tables must be evaluated for their effect on dynamic flight characteristics.

2) Helicopter training simulators are often developed years after the aircraft airworthiness flight test program has been conducted. In the future the simulator and aircraft manufacturers should work together in preparing a flight test program that will supply the needs of the simulator development program as well as the aircraft development program.

3) Methods must be developed to more readily identify inconsistent flight test data and assist the engineer in reconciling pilot opinion with FTD.

4) Expanded wind tunnel tests for aerodynamic forces and moments of aircraft components and their interactions would greatly enhance the accuracy of the baseline model. High-angle-of-attack, rearward, and sideward flight regimes often lack fuselage and empennage components.

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ACKNOWLEDGEMENTS

The authors wish to acknowledge the assistance of Stanley Briczinski (Staff Scientist), Skye Sweeney, and Tom Stockdale, all currently with Singer-Link, during development of the AUTOCOR program.

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