Real-Time Comparison of X-29A Flight Data and Simulation Data

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This paper presents a technique for comparing, in real time, the flight-test time histories for X-29A aircraft with time histories computed from linearized mathematical models. Such a comparison allows the flight-test personnel to verify that the aircraft is performing as predicted, to determine regions of nonlinear behavior, and to increase the rate of envelope expansion. The types of mathematical modeling and equipment required, the procedure used, and actual flight-test results are discussed.

Nomenclature

A_c = continuous-state transition matrix
A_d = discrete-state transition matrix
A_d' = discretized-state transition matrix of continuous model
a_n = normal acceleration
a_y = lateral acceleration
B_c = continuous-control derivative matrix
B_d = discrete-control derivative matrix
B_d' = discretized-control matrix of continuous model
F_d = discrete-control observation matrix
H_d = discrete-state observation matrix
p = roll rate
q = pitch rate
r = yaw rate
T = sampling interval
u = input vector
V = true airspeed
x = state vector
y = output vector
α = angle of attack
β = sideslip angle
δ_a = differential flap deflection
δ_c = canard deflection
δ_f = symmetric flap deflection
δ_{ps} = pitch stick deflection
δ_r = rudder deflection
δ_s = strake flap deflection
δ_{ys} = lateral stick deflection
θ = pitch-attitude angle
τ = variable of integration
ϕ = bank angle

Introduction

THE process of initial envelope clearance for research aircraft often requires new testing and monitoring techniques for flight safety. This has certainly been true for the X-29A forward-swept-wing technology demonstrator, an airplane that, since its first flight, has been flown with a negative static margin in excess of 35%. Faced with such a large static instability, the flight-control system design engineers placed rigorous requirements on dynamic stability, more specifically on the stability margins, of the augmented aircraft. Bosworth and West[1] describe the near-real-time determination of the stability margins from pilot-generated frequency sweeps during X-29A flights.

Immediate knowledge of the stability margins at any given flight condition greatly enhanced the confidence of the flight-test personnel in the adequate performance of the flight-control system. It was decided, however, that the frequency-domain measurements should be complemented by a comparison of the aircraft response in actual flight with the response of the simulator, preferably in real time or at least before the aircraft is taken to the next envelope clearance point. Typically, at any new test point, pilot stick pulses and doublets precede the frequency sweeps. Hence, the aircraft response to these pulses and doublets is available for comparison before the frequency response can be determined.

Obtaining the simulation response while the vehicle is in actual flight is simple, at least in principle. In reality, however, there may be many obstacles. For example, a suitable simulation of the test aircraft may not be collocated with the flight-test organization, or the required data link between the test aircraft telemetry system and the simulation may not exist.

This paper describes the time history comparison procedure using real-time flight data and simulation data and its usefulness to flight research. The technique described in this paper uses precomputed trim solutions of the nonlinear equations of motion and the linear, small-disturbance difference equations driven by either the pilot controls or the aerodynamic surfaces. These techniques are used routinely at the Dryden Flight Research Facility of NASA Ames Research Center (Ames-Dryden) and have contributed substantially to the efficiency and safety of the X-29A flight-research program.

Discussion

Benefits of Real-Time Transient Response Comparison

Direct comparison of the measured aircraft responses to those generated by a vehicle simulation, driven with identical pilot inputs, provides a wealth of timely information to the flight-test personnel. If this comparison can be made in real time in the form of overplotting the two kinds of responses, it becomes a useful flight test tool. The major benefits are summarized below.

1) Agreement between flight-test and linear simulation time

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history data strongly suggests that the vehicle dynamic properties in flight are the same as those predicted. This gives confidence that the flight condition is safe, and testing can proceed immediately to the next test point without waiting for the results of postflight processing of the data, which might take several days. Lack of agreement would indicate the need for an immediate halt in further testing until the cause of the discrepancy is found.

2) Regions of nonlinear behavior of the aircraft can be readily determined. For example, surface rate limits show up dramatically in the flight data when compared to the linearized simulation response. Knowing when the vehicle exhibits nonlinear behavior is useful in interpreting differences among results from other data analysis procedures, such as frequency response methods or postflight parameter estimation.

3) Control-system design is often based on a valid linear aircraft mathematical model. Until flight data become available, the linear mathematical model can only be validated against the full, nonlinear simulation. The success of the control-system design depends to a large degree on how accurately the linear model predicts vehicle response. When flight data are available, the validation of the linear model can be performed against actual flight data. If only a nonlinear aircraft model will accurately predict certain kinds of vehicle responses, those responses must be carefully simulated before flight using a full, nonlinear simulation.

Mathematical Model

The ultimate success of the real-time comparison technique depends on a sufficiently detailed and accurate mathematical model. For the X-29A aircraft, this model is obtained by linearizing the nonlinear equations of motion about a trimmed flight-path, such as straight-and-level 1-g flight or any quasi-steady-state flight path, such as a symmetric pullup or a constant-gravity turn. To date, the linearization for this procedure has only been done about a straight-and-level 1-g flight path.

Obtaining the linear equations of motion requires the Mach number, altitude, and aircraft weight at a particular test point. The control surfaces are then adjusted in the nonlinear model until steady level flight is obtained, that is, the sideslip angle and all accelerations and angular velocities are zero. This procedure is complicated because the X-29A aircraft uses three kinds of surfaces for pitch control: canards, strake flaps, and full-span flaperons. The linearized equations of motion are subsequently obtained by numerical differentiation about the trimmed flight path. The flight conditions for each stabilized test point are required before each flight. In a well-planned test program, this usually is not a problem.

Because the unaugmented X-29A aircraft is statically unstable in the pitch axis, initial attempts to bypass the control system and to use the telemetered aerodynamic surface positions to drive the simulation were not successful. Any small measurement errors in the surface positions or in the numerical differentiation cause the linear simulation to diverge quickly from the flight time history.

Subsequently, the linearized equations of motion were augmented by the mathematical model of the flight-control system. To insure that the augmented model approximates the closed-loop system as closely as possible, mathematical models of the actuators, sensors, notch filters, anti-aliasing filters, and a pure time delay are included in the flight-control system. Unsteady aerodynamics and structural modes are outside of the frequency range of interest and therefore are not included in the model. Despite this, the procedure resulted in a 48th-order augmented linear system of the form

$$x[(n+1)T] = A_d x(nT) + B_d u(nT) \tag{1}$$

$$y(nT) = H_d x(nT) \tag{2}$$

where the A_d and B_d are computed in the program CONTROL.[2] This program discretizes the continuous part of the model by performing the operations

$$A_d' = e^{A_c T}$$

$$B_d' = \int_0^T \exp[A_c(T-\tau)]\, \mathrm{d}\tau B_c$$

where T of the digital flight-control system is 0.025 s.

The program then augments A_d' and B_d' with the discrete dynamics of the flight-control system. Figure 1 illustrates the continuous and discrete parts of the longitudinal model.

The resulting linear difference equations representing the complete pitch-axis dynamics of the X-29A aircraft are driven by the pitch stick position. Because the stick position telemetered from the aircraft does not include the effect of a small deadband of the onboard flight-control system, this deadband must be modeled on the ground before routing the pitch stick position to the difference equations. The deadband is the only nonlinear element in the combined mathematical model. Outputs from the linear simulation are time histories (e.g., pitch rate) that can be directly compared to the flight time histories.

An alternate procedure is to model the unaugmented X-29A aircraft and to drive the resulting fourth-order linear model of the rigid aircraft pitch dynamics with measured surface positions. As mentioned earlier, this was unsuccessful because the vehicle is unstable.

The lateral-directional dynamics of the unaugmented X-29A aircraft are relatively conventional (i.e., stable) and therefore do not require the inclusion of the lateral-directional flight-control system. This resulted in a considerably simpler system. In this case, the linearized rigid-body equations of motion, of only the fourth order, are driven using measured

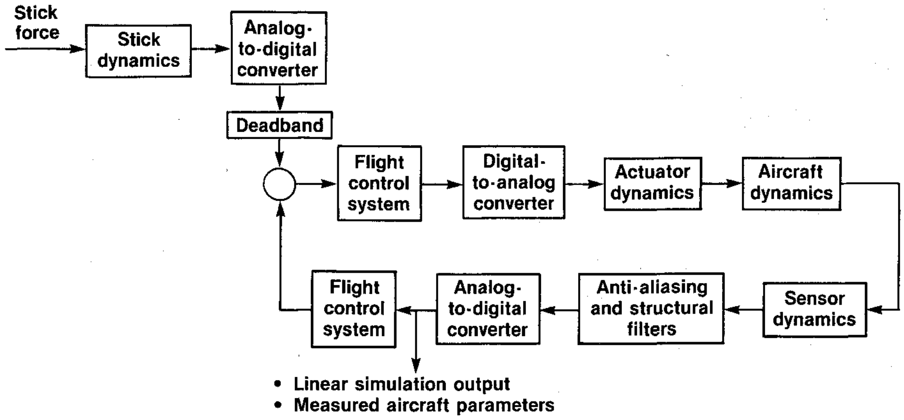

Fig. 1 Schematic of linearized longitudinal dynamics.

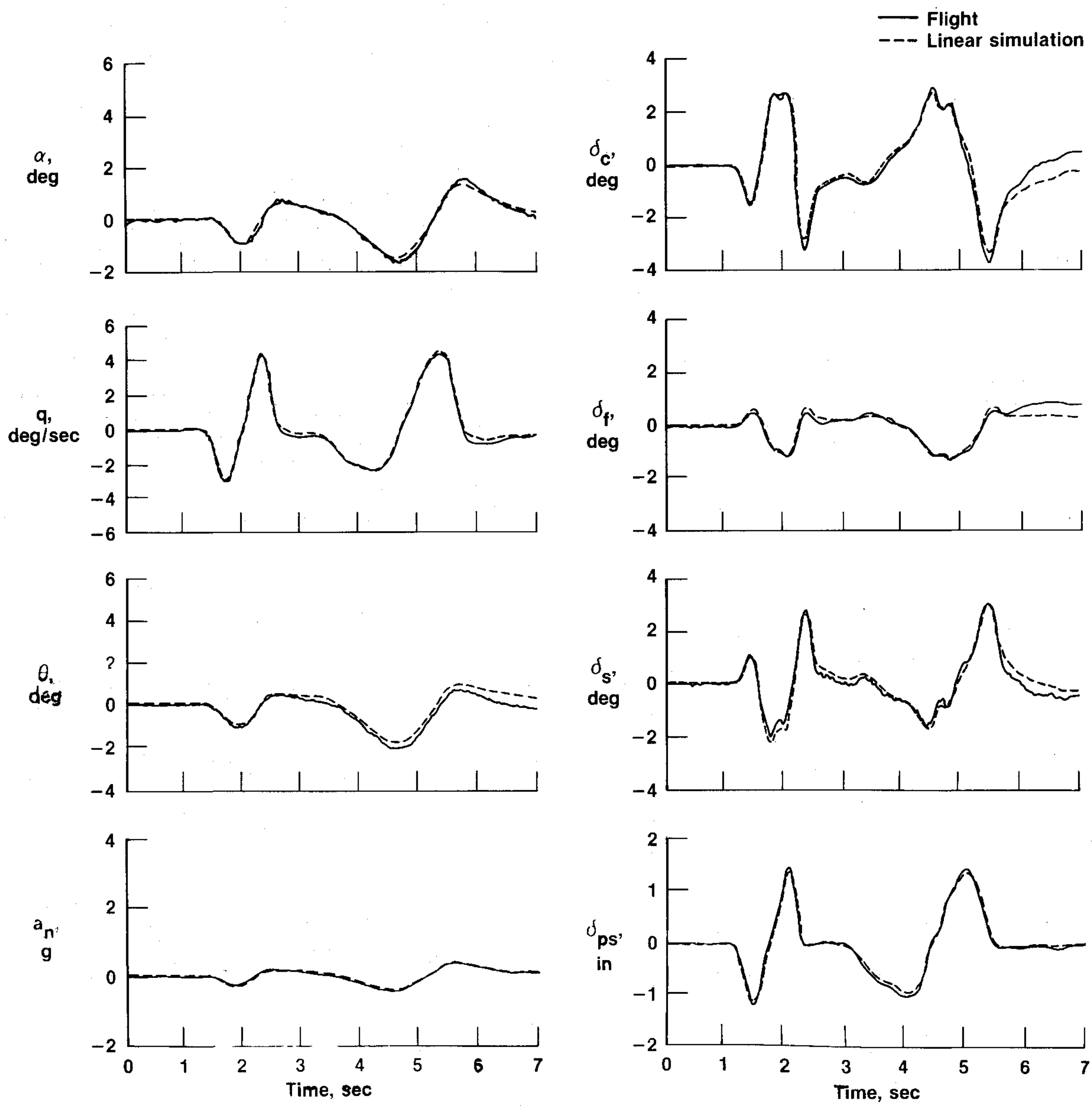

Fig. 2 Real-time longitudinal overplots.

aircraft surface positions:

$$x[(n+1)T] = A_d x(nT) + B_d u(nT) \tag{3}$$

$$y(nT) = Hx(nT) + Fu(nT) \tag{4}$$

where H and F are the state and control observation matrices, respectively. Using this approach, however, only serves as a check of the aerodynamics; it provides no information on the flight-control system or nonlinearities in the system.

Initialization of Flight and Simulation Data

This procedure requires the pilot to stabilize the vehicle on a particular reference flight condition (e.g., unaccelerated straight-and-level flight). On this reference flight condition, the vehicle states and controls commonly have constant trim values. In the linear simulation models, the state and control vectors represent perturbations from the trim conditions.

Two possibilities for displaying the time histories exist:

1) Add the trim values of the real aircraft states and controls to the linear simulation at each computational cycle.

2) Subtract the trim values of the aircraft states and controls from each successive measurement, thereby "initializing" each aircraft state and control variable to the initial zero state and control of the difference equations.

The second procedure is used because it allows for favorable scaling of the overplots. This scaling displays more details of the flight data than the conventional strip chart, which must be scaled to the maximum anticipated values for the whole flight.

The trim values of the angle of attack and surface positions obtained in flight may, and frequently do, differ slightly from the precomputed values of the simulation. The reasons for such differences could be many, such as weight differences, differences in zero-lift pitching moment, and nonstandard day conditions. Because the overall objective is a quick look at the vehicle dynamic responses, such as frequencies and damping ratios, the slight differences in trim conditions do not have a significant effect on this procedure.

Comparison Procedure

The time history overplot procedure makes use of specific capabilities of the Ames-Dryden Western Aeronautical Test Range; however, it is sufficiently general to be adapted by any flight-test organization.

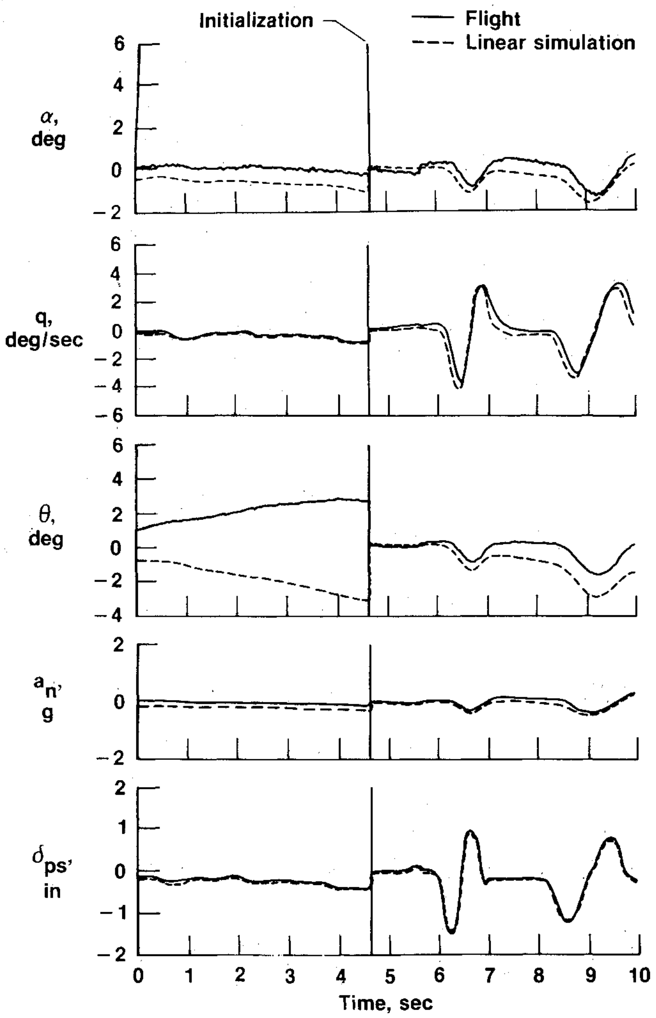

Fig. 3 Initialization of flight data and simulation data.

During flight, the data stream from the aircraft is processed and stored in a data pool with access to multiple users. As soon as the pilot stick signal from a pitch pulse or doublet is available, it is used to compute the predicted aircraft states and observables according to Eqs. (1) and (2). For a lateral-directional maneuver, the aerodynamic surface positions and Eqs. (3) and (4) are used. The computations yield the predicted response variables whose measured counterparts are available from the data pool. After the appropriate responses are paired, the flight and linear simulation results are routed to a color-graphics terminal for real-time display. This is accomplished with the update rate of the flight-control system (0.025 s). When the next set of data is available from the aircraft, the procedure is repeated. This process continues until a time history trace is produced. An example of a time history display resulting from a pitch doublet is shown in Fig. 2.

A desirable feature of this procedure is the ability to initialize both the flight data and the simulator predictions before a maneuver (Fig. 3). The control room engineer monitors the aircraft time histories on the graphics terminal. On a call from the pilot, or when the aircraft appears to be trimmed, the engineer simultaneously selects the precomputed difference equations and initializes the flight data. If necessary, his selection can be easily repeated. A flowchart of the real-time operations is presented in Fig. 4.

For the comparison between the linear simulation and the actual aircraft flight, the filtered and digitized aircraft parameters and the corresponding parameters from the simulation are used as shown in Fig. 1. The definitions of these parameters are longitudinal axis: α, deg; q, deg/s; θ, deg; a_n, g; δ_c, deg; δ_f, deg; δ_s, deg; δ_{ps}, in.; and lateral-directional axis: β, deg; p, deg/s; r, deg/s; ϕ, deg; a_y, g; δ_a, deg; δ_r, deg; δ_{ys}, in.

The simulation time histories and flight time histories are overplotted in real time on a color-graphics terminal. The graphics terminal can simultaneously display overplots of eight parameters. This allows real-time decisions to be made for the operation of the flight-control system and permits a check of the fidelity of the linearized aerodynamics. When the maneuver is completed, the simulation is halted and hard copies of all responses are produced for further evaluation.

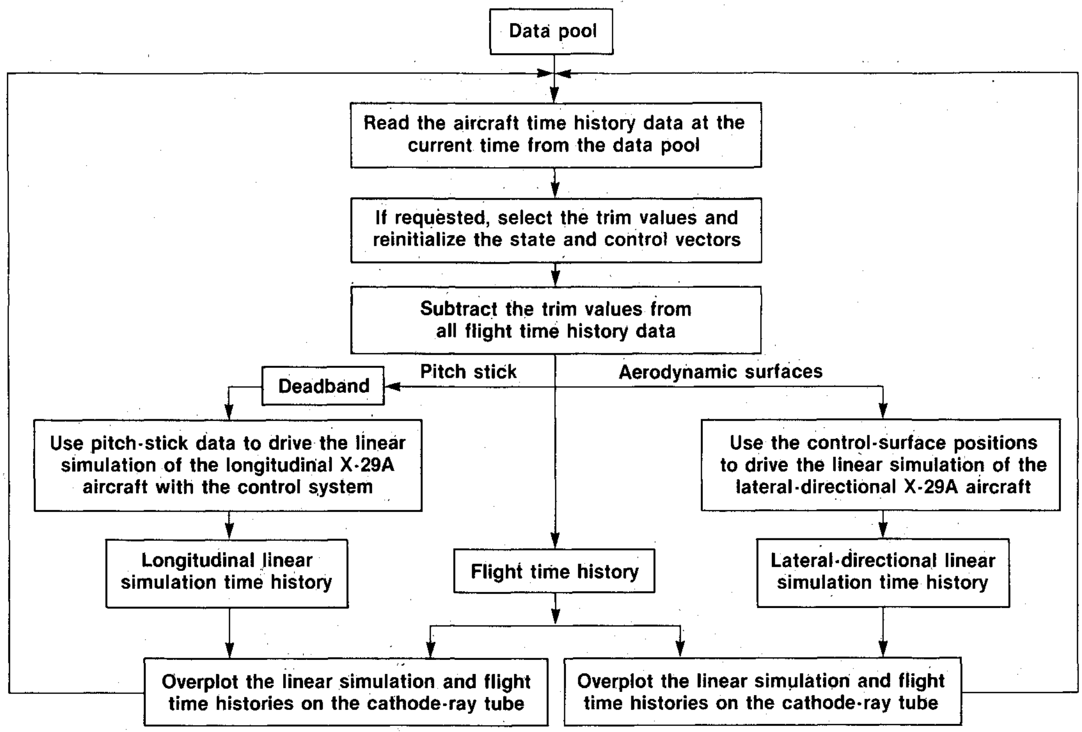

Fig. 4 Flowchart of real-time overplot procedure.

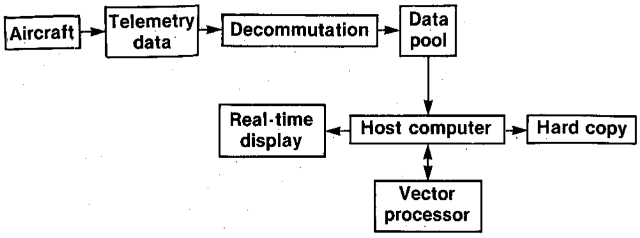

Fig. 5 Hardware requirements.

Computation and Display Requirements

The running of a full, nonlinear, six-degree-of-freedom simulation in a ground computer is possible in principle. However, the routine data-processing requirements associated with the ongoing flight test and other real-time processes would task the existing facility beyond its present capability. The precomputed trim solutions and linear difference equations of motion are therefore used. Processing of the linear difference equations involves only vector and matrix algebraic computations that can be done efficiently in a vector processor. The

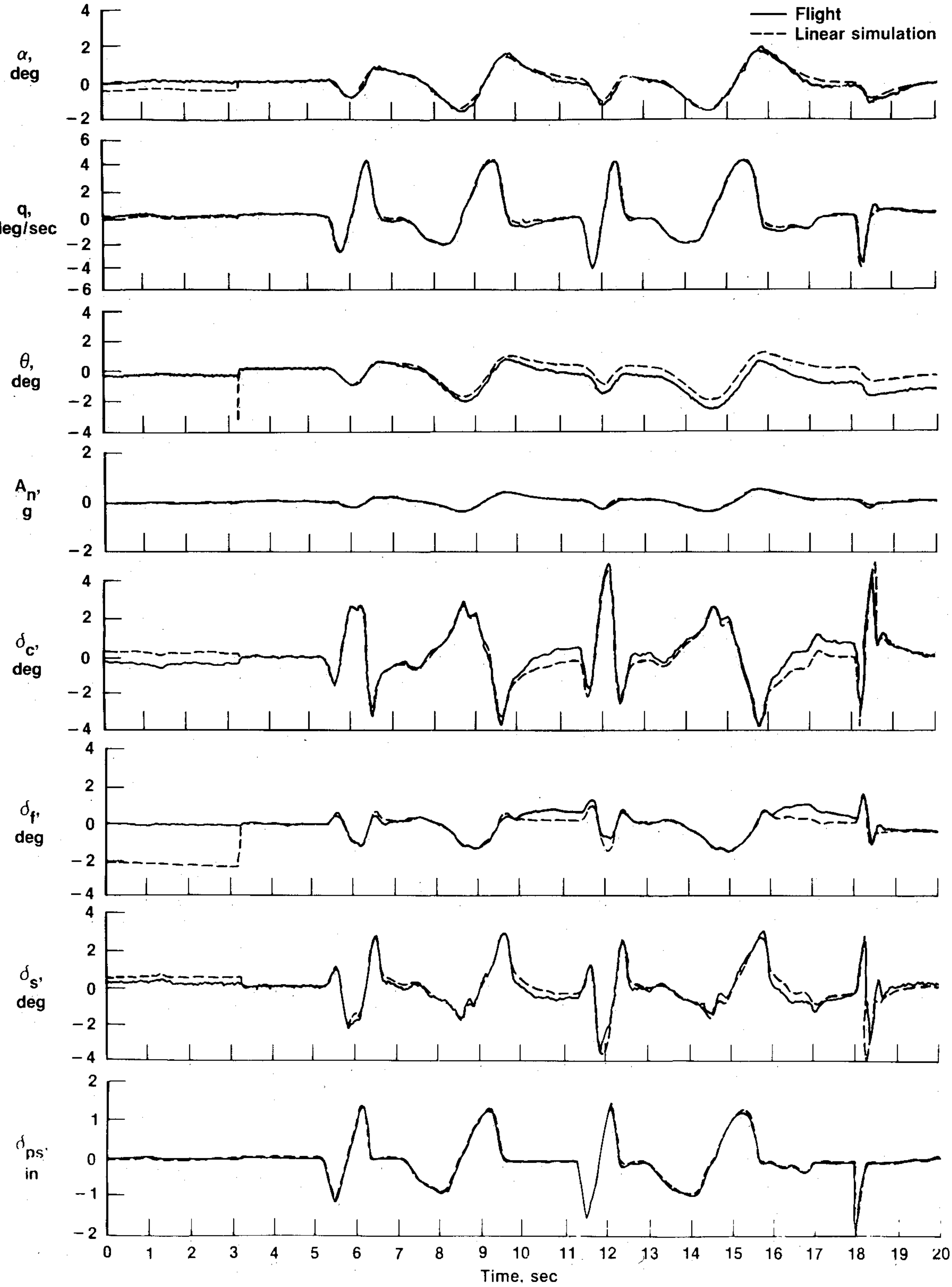

Fig. 6 Time history comparison of longitudinal real-time linear simulation data and flight data.

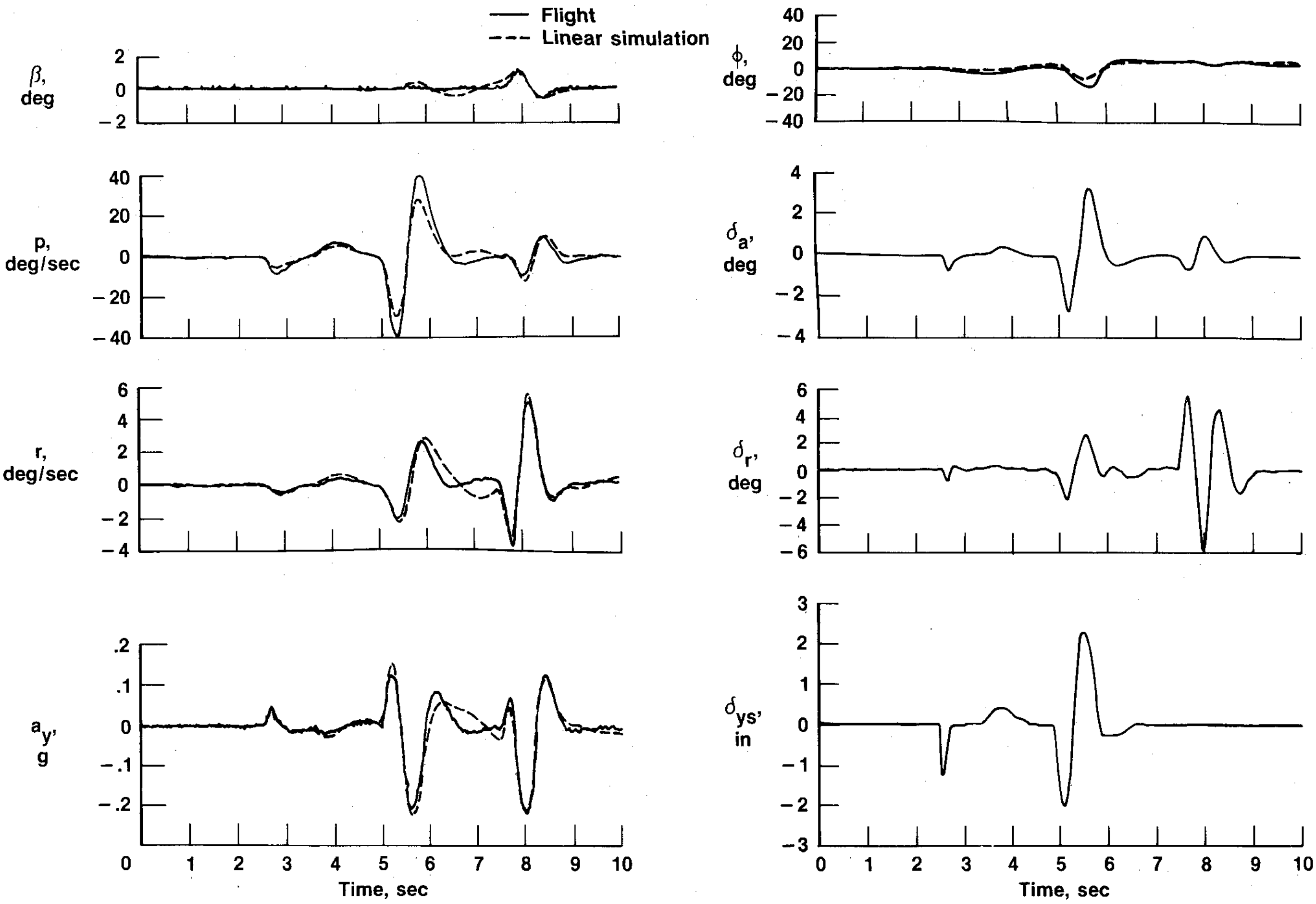

Fig. 7 Time history comparison of lateral-directional real-time linear simulation data and flight data.

full, nonlinear, six-degree-of-freedom equations of motion are not as easily implemented on a vector processor; additional capability from the ground-based computers is required.

A vector processor is a special processor that is capable of performing parallel operations on large arrays of data. The vector processor being used for the X-29A simulation has a capability of 15 million floating-point operations/s and is specially suited for vector and matrix algebra. The host computer for the vector processor is capable of 4 million instructions/s and operates with a 75-ns frame time.

In addition to the vector processor and host computer, a high-resolution color-graphics station is used with the capability of displaying multiple time history overplots in real time. A laser printer produces hard copies of all output channels shortly after the test maneuver is completed. Figure 5 illustrates the interfacing between the major components involved in the comparison.

Results

A time history comparison from a recent X-29A flight test (Fig. 6) shows that the flight data were initialized and the simulation restarted at approximately 3.2 s. Both the X-29A aircraft and the simulation responded to identical pilot inputs, the first of which was a fast pitch stick doublet beginning at 5 s. The maneuver was followed by a slower doublet beginning at 7 s. These two doublets were repeated by the pilot a few seconds later. A sharp nosedown stick pulse or "rap" was made at 18 s. If one considers the length of time, the simulation time histories track the airplane response remarkably well. The only notable exception was the pitch-attitude trace; this discrepancy is the result of a small initialization error in pitch rate.

The only significant discrepancy between the linear prediction and flight data occurs in the pitch-rate trace at approximately 18.5 s. This discrepancy is due to the fact that the X-29A strake flap actuators were rate-saturated at this time, whereas the entirely linear model was free of this nonlinearity. The surface rates are computed during the maneuvers but are not displayed in real time. They are, however, available after the maneuver in hard-copy form.

Figure 7 is a lateral-directional overplot from a recent flight test. The flight data were initialized and the simulation was restarted just before the beginning of the comparison. The pilot input consisted of a lateral stick pulse at 2.5 s followed by a lateral stick doublet beginning at 4.8 s. A directional doublet was input beginning at 7.5 s. In this case, the linear model was driven using the aerodynamic surface positions. For this maneuver, the linear model does not adequately predict the aircraft responses. Hence, envelope expansion should proceed more cautiously because the aircraft may not be performing as predicted. Postflight parameter identification confirmed that several lateral-directional derivatives were in error in the model. The spikes appearing in the flight data of the sideslip-angle trace are the result of noisy aircraft measurements.

Figure 8 shows a comparison of the full six-degree-of-freedom simulation and the flight data, computed postflight, for the pitch-axis maneuver of Fig. 6. The flight data have been initialized to the simulation initial conditions. The linear simulation with flight data (Fig. 6) compared with the nonlinear simulation with flight data (Fig. 8) illustrates the capability of the linear model to predict the aircraft responses to a high degree of accuracy, with the obvious limitations inherent in a linear model. As pointed out earlier, however, these limitations can be beneficial. As computer capabilities increase, it will be possible to compare the flight-test data with the full,

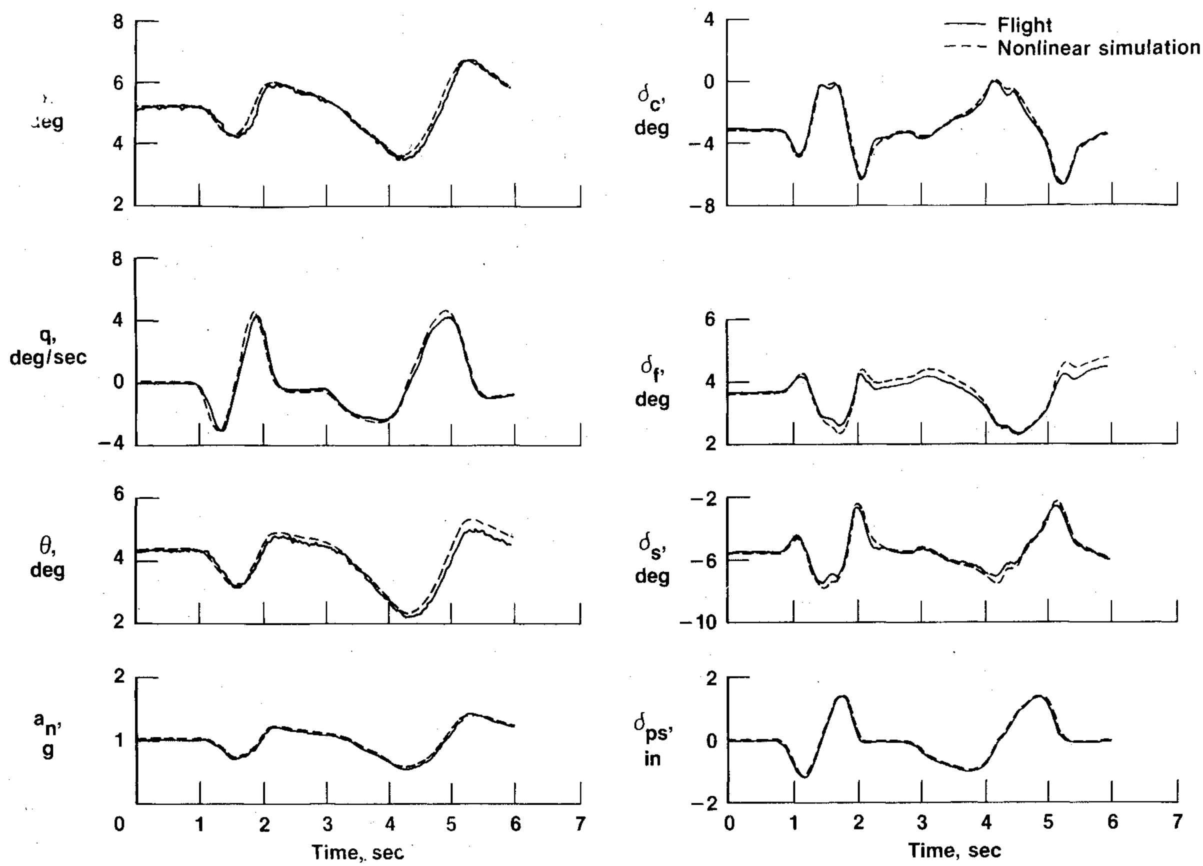

Fig. 8 Time history comparison of real-time nonlinear simulation data and flight data.

nonlinear, six-degree-of-freedom simulation in real time, resulting in improved comparison capability. This improved capability would allow maneuvers such as wind-up turns where lateral and longitudinal dynamics are coupled as well as large-amplitude maneuvers which may involve a change in the flight condition.

It should be emphasized that the purpose of the real-time comparison is not to validate the aerodynamic data base of the simulation or to determine which aerodynamic derivative may be incorrectly modeled in the data base. The reason for displaying time histories such as these, in real time, is to see whether gross discrepancies between the airplane and the mathematical model develop at any time during the envelope clearance process.

The additional amount of information compared to that of conventional strip charts allows for more rapid clearance of a flight-test point. As a result, the speed of envelope expansion could be substantially increased. In addition, inherent discrepancies in the model, rate saturation (as mentioned above), and surface limits can be easily identified using the real-time overplot comparison. Also, if the overplot comparison is a good one, linear models can be validated.

Conclusions

During the X-29A flight-test program, a significant new flight-testing tool was developed. Specifically, the benefits of real-time comparison of the flight and simulation data have been demonstrated. The method is effective in immediately displaying any gross differences between actual and predicted responses and in recognizing regions of nonlinear aircraft behavior. This allows for quicker, safer envelope expansion and greatly reduces the required amount of postflight data analysis.

References

[1]Bosworth, J. T. and West, J. C., "Real-Time Open-Loop Frequency Response Analysis of Flight Test Data," AIAA Paper 86-9738, April 1986.

[2]Edwards, J. W., "A FORTRAN Program for the Analysis of Linear Continuous and Sampled-Data Systems," NASA TM X-56038, 1976.