An Advanced Method for Airborne Simulation

HERMAN A. REDIESS* AND DWAIN A. DEETS†
NASA Flight Research Center, Edwards, Calif.

A model-controlled-system method for airborne simulation that overcomes some disadvantages of present variable-stability airplanes has been studied analytically and proved feasible. This new approach has been a natural outgrowth of the development of model adaptive control systems and uses a similar model-following concept. Satisfactory matching of specific motion parameters can be obtained for model frequencies at least up to the natural frequency of the base airplane used for the airborne simulator. Time histories from analog studies of a simulator using a model-controlled system in a small subsonic jet transport and using a hypothetical supersonic transport as the model are presented as examples of the simulation performance expected. In a general discussion of airborne simulation, it is observed that the motion of a specific aircraft cannot be matched completely with an airborne simulator, except at certain specific conditions, if the number of independent control devices for angular and linear motion is less than the number of corresponding degrees of freedom to be simulated. However, airborne simulators can be valuable research and pilot-training tools through proper choice of the motion parameters to be matched and by tailoring the program to the particular simulator used.

Nomenclature

K_q = response-feedback gain, δ_e/q, deg/deg/sec
K_α = response-feedback gain, δ_e/α, deg/deg
M_q = pitching moment due to pitch rate
M_α = pitching moment due to angle of attack
M_{δ_e} = pitching moment due to elevator deflection
n_{Y_p} = acceleration at the pilot's location along Y axis, g
n_Z = acceleration at center of gravity along Z axis, g
n_{Z_p} = acceleration at the pilot's location along Z axis, g
p = rolling angular velocity, deg/sec
q = pitching angular velocity, deg/sec
r = yawing angular velocity, deg/sec
s = Laplace transform variable
Y, Z = reference body axes centered at the center of gravity
α = angle of attack, deg
β = angle of sideslip, deg
Δ = incremental change
δ_e = elevator deflection, deg
δ_r = rudder deflection, deg
θ = angular displacement in pitch, deg
φ = roll angle, deg
ω = longitudinal short-period frequency of the base airplane

Subscripts

m = model
$\left|\frac{n_{Z_p}}{n_{Z_{pm}}}\right|, \left|\frac{p}{p_m}\right|, \left|\frac{\beta}{\beta_m}\right|$ = frequency-response amplitude ratios for the transfer functions $n_{Z_p}(s)/n_{Z_{pm}}(s)$, $p(s)/p_m(s)$, and $\beta(s)/\beta_m(s)$, respectively.

Introduction

SIMULATORS have been used extensively over the past 10 to 15 years in the design and development of aircraft, particularly in the area of handling qualities. In general, the simulators can be grouped into three major categories: stationary ground based, moving ground based, and airborne. Each type has advantages and disadvantages and associated fidelity of simulation. The desire for increased simulator realism prompted the development of the airborne simulator which, if properly mechanized, can provide the correct motion and visual cues for the pilot and, equally important, the actual flight environment.

Airborne simulation has been accomplished by utilizing a variety of vehicles. Many types of research and pilot-training airborne vehicles, such as fixed- and rotary-wing variable-stability aircraft, variable-control-feel-system aircraft, and even standard production airplanes, have been used to simulate other aircraft; however, the terms "in-flight" or "airborne" simulator usually refer to a variable-stability airplane. This type of simulator has been mechanized utilizing a response-feedback system and, more recently, an advanced concept, the model-controlled system. The response-feedback system is based on the same concept as a simple damper system to alter the stability and control of the basic airplane. Two simulators that utilize the model-controlled concept are in flight status.‡

The NASA Flight Research Center has conducted and sponsored§ studies leading to the design and development of a general-purpose airborne simulator (GPAS) to support the supersonic-transport program and to perform general research. This paper presents some of the results of these studies. The response-feedback and the model-controlled concepts for an airborne simulator are discussed and evaluated. The model-following performance of the system designed for the GPAS and other results believed to be generally applicable are also presented.

Response-Feedback System

Many of the variable-stability airplanes that have been used as airborne simulators were mechanized with response-feedback systems. With this type of system, the static stability and damping of the base airplane are augmented by a displacement and rate-feedback signal[2] as shown for the longitudinal mode in Fig. 1. An effective increment in static stability M_α is obtained as

$$\Delta M_\alpha \alpha = M_{\delta_e} (\delta_e/\alpha)\ \alpha = M_{\delta_e} K_\alpha \alpha$$

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* Head, Airborne Simulation Section. Member AIAA.
† Aerospace Technologist.

‡ The National Research Laboratories, Ottawa, Canada, have installed a model-controlled system in an H-13G helicopter.[1] Also, Honeywell, Inc., has installed a modified MH-90 model adaptive control system in an F-101 airplane. The model can be varied, which gives it a variable-stability capability.

§ Cornell Aeronautical Laboratory, Inc., and the Los Angeles Division of North American Aviation, Inc., have performed preliminary design studies of the GPAS under a NASA contract.

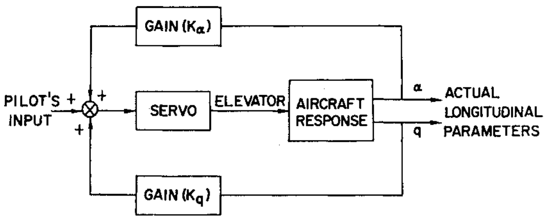


Fig. 1 Response-feedback system.

where M_{δ_e} is the pitching moment due to elevator deflections, and an effective increment in M_q or damping is obtained similarly. The mechanization of the lateral-directional modes is similar; however, the calibration or setup for a test condition is somewhat more complex because of the coupling of the airplane roll and yaw modes.

Airborne simulators of the response-feedback type are best suited for performing general research on vehicle handling qualities, such as an evaluation of the effect of stability and damping,[3,4] roll-to-yaw ratio,[5,6] and the ratio of roll-control frequency to basic natural frequency.[7] During the referenced investigations, a range of variables was investigated rather than a specific vehicle simulation. Relatively few research programs[8–10] involving simulation of specific vehicles have been conducted. Experience has proved that these types of programs involve considerable setup and calibration time on a response-feedback system.

Some disadvantages of this type of system for simulating a specific vehicle are apparent from its mechanization. The simulation is derived from the base airplane by adding incremental changes to the stability parameters of the base airplane. Thus, the stability and control characteristics, as well as the flight condition of the base airplane, must be known accurately in order to calculate the required feedback gain settings.

Time histories of an ideal response-feedback system for the longitudinal mode of a variable-stability airplane mechanized on an analog computer are presented in Fig. 2. The simulation task was to match the desired pitch-rate response shown by the solid line. The dashed line is the actual response of the variable-stability airplane. The upper plot is the type of simulation that would be obtainable if the stability parameters of the base airplane were known accurately when the feedback gains were calculated. The lower plot shows the mismatch that would result if the static-stability parameter M_α were in error by only 10%, which is, of course, quite possible. Note that the frequency, damping, and amplitude are significantly different from the desired motion. This was a simple example to illustrate the problem. If there were errors in the damping or control parameters as well, the mismatch could be even worse. The simulation could be improved to a point comparable to that in the upper plot by a trial-and-error adjustment of the feedback gains; however, this would require an extensive flight program if many flight conditions were to be used.

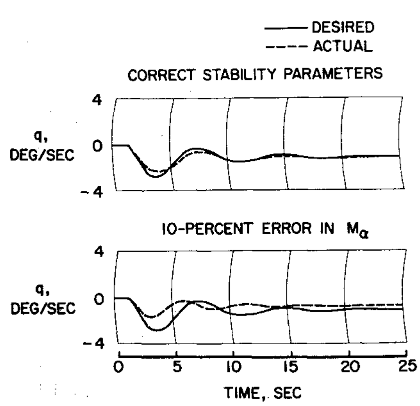


Fig. 2 Response-feedback-system performance.

To illustrate the magnitude of this task, the time that would be required to calibrate a variable-stability airplane with six feedback loops for all possible combinations of gains at only one flight condition was calculated. Assuming that the airplane could fly continuously for 6 hours every working day of a year, 22 years would be required to complete the calibration. Obviously, variable-stability airplanes are not operated in this manner; instead, only a few combinations of flight conditions and gain settings are calibrated, thus pinpointing the area of interest for a particular investigation.

Another disadvantage of the response-feedback system is that, once the setup is attained, a measure of the exact characteristics simulated is difficult and is obtained only by using the usual methods of extracting aircraft flight derivatives. This type of system is relatively inflexible. Programs with minimal changes or of limited scope are acceptable, but programs that require many changes for exact simulations can result in a high percentage of downtime for setup or calibration. More complete simulation programs, such as varying the stability as a function of flight conditions or angle of attack, would require a rather complex mechanization using the response-feedback approach and an extremely complicated and time-consuming calibration.

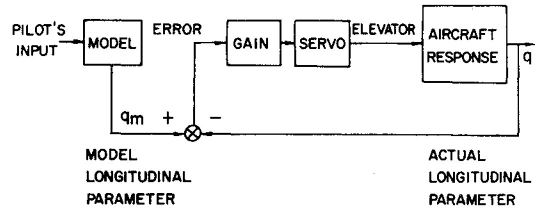


Fig. 3 Model-controlled system.

Model-Controlled System

The difficulties in using the response-feedback type of system for airborne simulation of a specific vehicle, and the desire to provide a more complete and flexible simulation in flight, generated interest at the Flight Research Center in a new approach to airborne simulation systems. The model-controlled-system approach has been a natural outgrowth of the development of model adaptive control systems and has been the subject of several recent studies.¶

A model-controlled system can be implemented in several different forms, as can an adaptive control system. The form of the model-controlled system studied is referred to as the prefilter approach and is shown conceptually for the

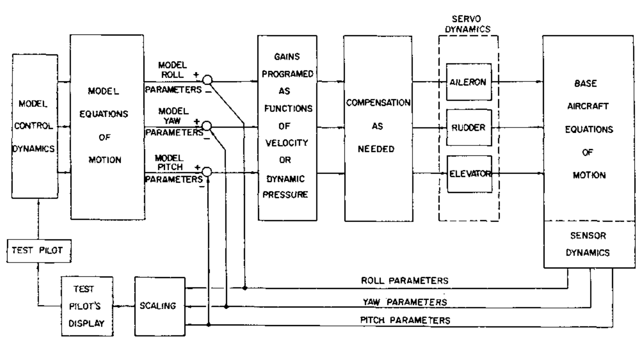


Fig. 4 Model-controlled airborne simulation system studied.

¶ In addition to Ref. 11, investigations (unpublished) of the model-controlled-system approach have been made by Cornell Aeronautical Laboratory, Inc., Honeywell, Inc., Sperry Phoenix Co., and Systems Technology, Inc.

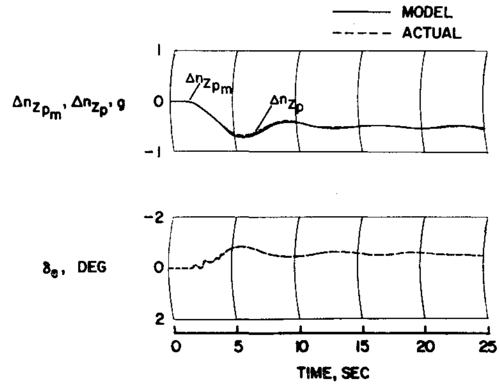


Fig. 5 Model-following performance of n_{z_p} control loop. Pilot input: 2° elevator.

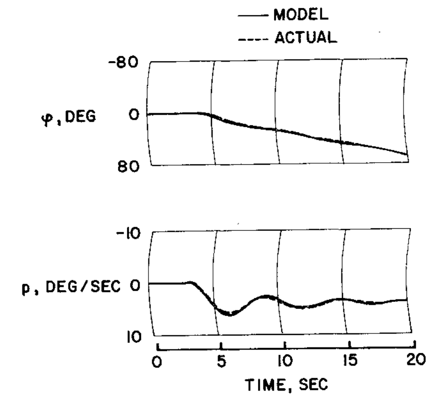


Fig. 7 Model-following performance of roll-rate control loop. Pilot input: 2° rudder.

longitudinal mode in Fig. 3. The system consists of an electronic model of the desired pitch response to a pilot's elevator-control input and a high-gain closed-loop system that drives the base airplane's pitch response to follow that of the model. The model can be as simple as a first-order transfer function mechanized with a passive network or as complex as six-degree-of-freedom equations of motion with nonlinear coefficients programed on an airborne computer.

During the preliminary design studies of the GPAS, several control loops for each of the primary control devices (ailerons, elevator, and rudder) were designed and then tested on an analog mechanization of the GPAS. Figure 4 is a functional block diagram of the model-controlled simulation system mechanized on an analog computer. The base airplane for these studies was a small subsonic jet transport, and the model was a hypothetical supersonic transport. Fixed compensation and programed gains were required to give satisfactory model-following performance throughout the flight envelope of the base airplane. First-order-lag transfer functions were used to represent the control-system dynamics of the model in most cases.

The results of these studies for three control loops are presented in order to illustrate the model-following performance that could be expected with this type of system. Normal acceleration at the pilot's location n_{Zp}, the angle of sideslip β, and roll rate p were used as the pitch, yaw, and roll parameters, respectively, in the system shown in Fig. 4. Time histories showing the model-following performance for each of these three control loops are presented in Figs. 5, 6, and 7. These time histories are for a supersonic-transport model with a longitudinal short-period frequency of 0.18 cps and a Dutch roll frequency of 0.17 cps. The natural frequencies of the longitudinal short period and lateral Dutch roll modes are 0.7 cps and 0.5 cps, respectively, for the base airplane. In each figure the actual base-airplane response is superimposed on the model response, and in each instance the simulation is very close. The amount of elevator and rudder of the base airplane required to make this match in n_{Zp} and β is shown by the lower plots in Figs. 5 and 6, respectively. Only small control-surface displacements and relatively low surface rates are required, even though the maneuvers are sizable.

The error between the model and actual response has been calculated for each of the three closed loops at gains that gave good model-following for the supersonic-transport simulation. These errors, in terms of time lag and amplitude error, are presented as a function of model frequency in Figs. 8, 9, and 10 for n_{Zp}, angle of sideslip, and roll-rate loops, respectively. According to Ref. 12, the tracking time (or time lag) of a pilot in a compensatory tracking task is between 0.12 and 0.18 sec. Using this criterion, the time lags that occur in each of the loops of Figs. 8, 9, and 10 are considered to be acceptable. The amplitude errors shown in the lower plots of these figures are 20% or less; however, at any specified model frequency, the amplitude of the error can be eliminated by using an input gain on the model-command parameter n_{Zpm}, β_m, or p_m.

In general, increasing the closed-loop gain for any of the loops will reduce the error in that loop; however, the gain must remain less than the critical value at which some mode becomes unstable. This critical value varies with the base airplane's flight condition. As an example, Fig. 11 shows the variation of the normal-acceleration gain with dynamic pressure for an elevator control loop using the normal acceleration at the center of gravity as the command parameter. A system stability boundary can be drawn, as shown, as a function of dynamic pressure. The gain must remain lower than this boundary to maintain stability. Values below but close to the boundary cause low system stability; therefore, a satisfactory gain must be somewhat lower than the boundary. This figure shows that, in order to have a satisfactory gain at every dynamic pressure, it is necessary to

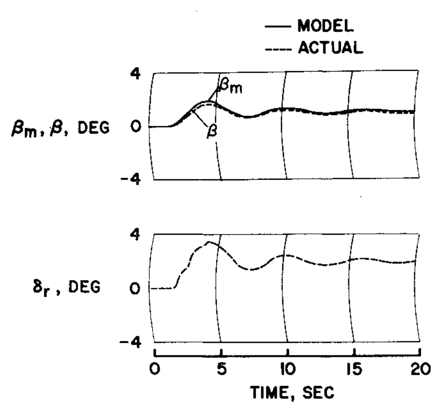


Fig. 6 Model-following performance of angle-of-sideslip control loop. Pilot input: 1° rudder.

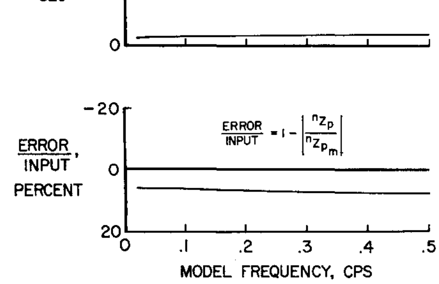


Fig. 8 Error in n_{z_p} as function of model frequency.

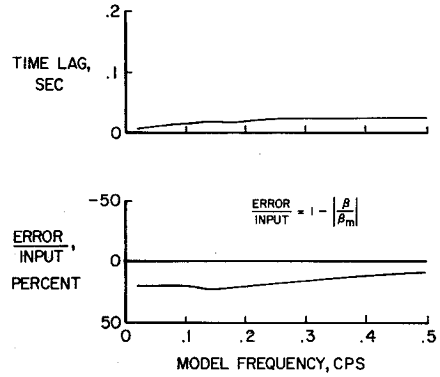


Fig. 9 Error in sideslip angle as a function of model frequency.

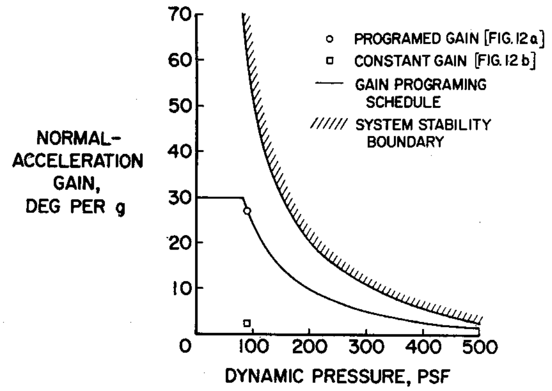


Fig. 11 Variation of normal-acceleration gain with dynamic pressure.

adjust the closed-loop gain when the flight condition changes. There are several methods that could be used to adjust the gain. If only a small change in dynamic pressure is required in any given simulation, two or three gain levels on a manual step switch would be adequate. A self-adaptive gain changer would do the job well but would probably be more complex than necessary. The GPAS studies showed that a simple programing of gain with dynamic pressure, as shown in Fig. 11, was adequate for most of the control loops; for the other control loops, a similar programing with velocity was used. An adaptive system probably would not be required for any airborne simulator unless an extreme range of flight conditions was desired.

A constant gain for all flight conditions does not appear to be satisfactory for a general-purpose simulator. If a constant gain were used, it would have to be the lowest critical gain value shown in Fig. 11 so that no instabilities would occur. Although this low gain is adequate at the high dynamic pressures, it gives poor following performance at the low dynamic pressures. This point is illustrated in Fig. 12 by time histories taken at low dynamic pressures for two values of gain. The upper time history of Δn_z is for a value of gain corresponding to the circular symbol in Fig. 11, which is on the programed gain line. The bottom time history corresponds to the square symbol, having the low gain value that would be required if a constant gain were used for all flight conditions. The model-following performance for the constant gain is definitely not satisfactory. This shows clearly why some type of gain changing is required to keep the gain at a level that provides performance as good as that shown in the upper time history.

Thus far, the discussion has been restricted to relatively low model frequencies, less than the maximum bandwidth of the base airplane. If model frequencies greater than the base airplane's bandwidth are required, the base airplane acts as a filter to the control-surface inputs. This effect is shown in Fig. 13 for a pitch-attitude control loop. Note that an increased elevator magnitude is required with increasing frequency to maintain a pitch-attitude oscillation of relatively constant magnitude. The elevator may rate-limit or authority-limit at the higher frequencies, which would compromise the simulation.

Discussion of Airborne Simulation

From the preceding discussion, it is apparent that an airborne simulator can be designed that faithfully reproduces one motion parameter for each of the primary control surfaces; however, the response of the remaining uncontrolled degrees of freedom has not yet been considered. The discussion in this section applies to simulators utilizing the response-feedback system, as well as to the model-controlled system.

Variable-stability airplanes generally use only the three primary control surfaces as control devices for the variable-stability system. Since the number of degrees of freedom that can be simulated accurately is directly related to the number of independent control devices used, not all motion parameters can be matched simultaneously. The inability to match more degrees of freedom than the number of control devices available is illustrated in Figs. 14 and 15. Figure 14 presents a time history of the GPAS simulating a supersonic-transport-model response to an elevator step input for an n_{z_p} control loop. The normal acceleration at the pilot's location matches the model well, but the simulator pitch attitude is considerably different from that of the model. There are two reasons for this difference. In the airborne simulator the pilot is about one-fourth as far forward of the center of gravity as he is in the supersonic-transport model; thus, the effect of pitching due to normal acceleration

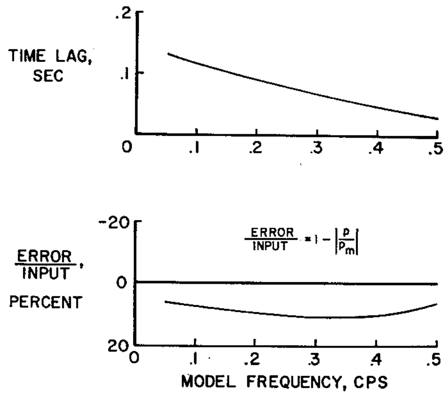
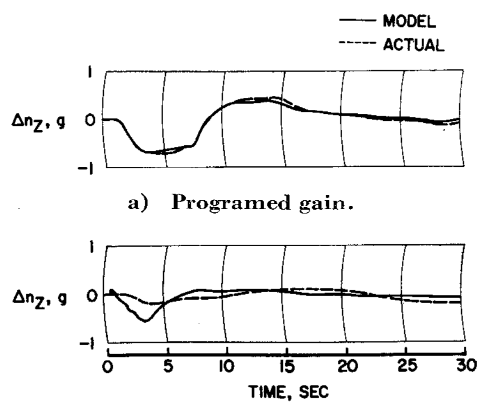


Fig. 10 Error in roll rate as function of model frequency.



b) Constant gain.

Fig. 12 Effect of gain on model-following performance.

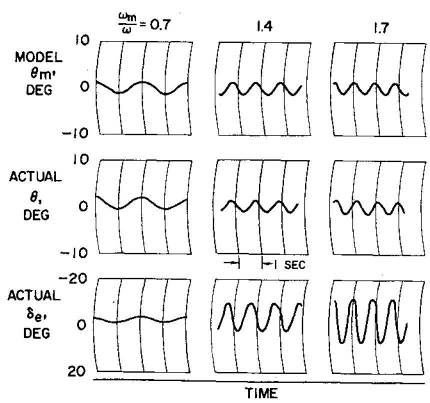


Fig. 13 **Effect of simulating frequencies higher than the natural frequency of the base airplane.**

is not as pronounced. Also, the supersonic-transport model and the airborne simulator have different aerodynamic characteristics and different flight conditions which, with matched accelerations, result in different attitudes.

For the simulation of instrument flight rules (IFR) piloting tasks in which the pitch attitude of the model can be presented to the pilot on an artificial horizon, the n_{Z_p} control loop could be used and would provide the pilot with the same acceleration as the model.

As another example, consider the simulation of an approach and landing task. For this piloting task, pitch attitude is the important outside visual cue and, therefore, a θ control loop should probably be used to provide the pilot with the correct pitch attitude. The normal acceleration changes would be small; thus, a small error in n_{Z_p} would not be critical.

Both pitch attitude and normal acceleration can be matched approximately with a single control device if the base airplane's flight condition can be selected so that the relationship between normal acceleration and pitch attitude is approximately the same as that for the model. Of course, this is not always possible; for example, in a landing simulation the flight condition cannot be changed.

If direct lift control, such as modified flaps, were used together with the elevator in the control system, it would be possible to match both pitch attitude and normal acceleration independently of the flight condition of the airborne simulator.

Figure 15 shows a simulation of the lateral-directional response of the supersonic-transport model to a 2° rudder input using n_{Y_p} and p control loops. Even when the pilot of the airborne simulator is much closer to the center of gravity than the pilot of the supersonic transport, the lateral acceleration of the airborne-simulator cockpit agrees well with that of the supersonic-transport model. However, the uncontrolled yaw parameters β and r do not match. As in the longitudinal case, proper selection of the flight condition for the airborne simulator could result in better agreement between the simulator yaw response and that of the supersonic-transport model. In the lateral-directional case, this solution is particularly important because of the impracticalities of providing an independent side-force control. If matching the sideslip angle is more important than lateral acceleration, angle-of-sideslip and roll-rate control loops can be used, but a compromise in matching the lateral acceleration must be accepted.

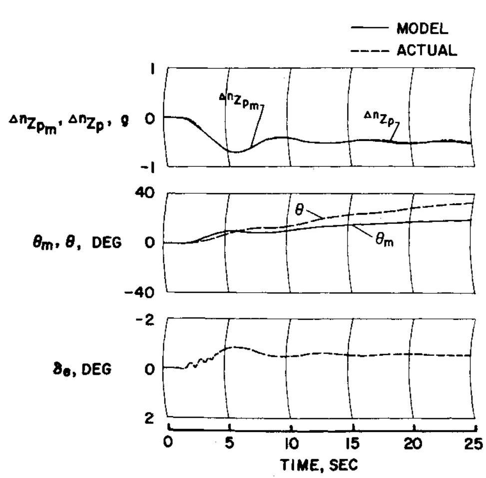


Fig. 14 **Model-following performance of n_{Z_p} control loop. Pilot input: 2° elevator.**

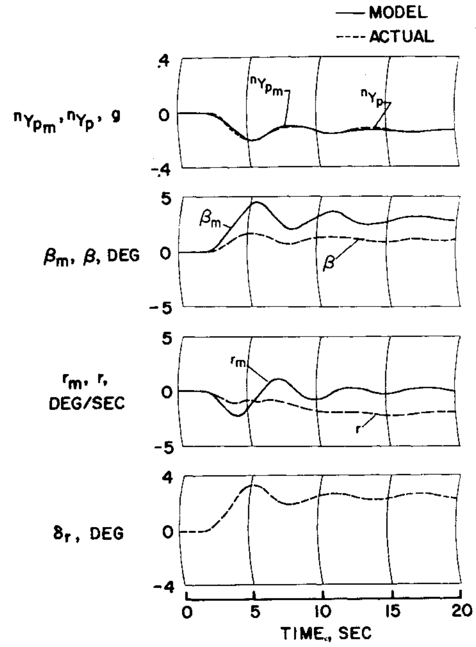


Fig. 15 **Model-following performance of n_{Y_p} and roll-rate control loops. Pilot input: 2° rudder.**

The choice of parameters to match, particularly in the lateral-directional case, is not clearly defined and may vary with the type of investigation. Further research is required to define the most important motion parameters to be simulated. Analysis of this problem will continue through the development of the GPAS and conclude with a flight-test program.

Concluding Remarks

Variable-stability and control-system airplanes are valuable research and pilot-training tools; however, the response-feedback type of system which has traditionally been used to vary the stability has some disadvantages. It is limited to relatively simple types of simulations and requires extensive setup time. Studies of a model-controlled system that would overcome these disadvantages show that satisfactory model-following can be obtained for model frequencies at least up to the natural frequency of the base airplane.

When the number of independent control devices (for example, aileron and elevator) for any type of airborne simulator is less than the number of degrees of freedom, it is impossible to match the motion completely, except at specific flight conditions of the base airplane. Additional research is needed to clarify better the most significant piloting cues for particular flight missions and airplane characteristics.

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Prediction of Flutter Onset Speed Based on Flight Testing at Subcritical Speeds

NORMAN H. ZIMMERMAN* AND JASON T. WEISSENBURGER†
McDonnell Aircraft Corporation, St. Louis, Mo.

The commonly employed damping vs velocity technique of flight flutter testing is known to have a number of shortcomings which adversely affect the reliability and safety of such testing. The damping measurements in themselves give little useful information beyond stating whether or not flutter was encountered at the test speeds flown; magnitude of the damping has all too frequently been a grossly misleading indication of flutter stability margin. A new technique of flight flutter testing is presented herein based on the use of a flutter stability parameter truly indicative of the state of flutter stability within the system. This flutter stability parameter is based on measured frequency and decay data taken during flight and clearly shows the erosion of flutter margin with increasing speed. Using this information, together with a flutter prediction technique also presented herein, it is possible to predict the behavior of the flutter margin at speeds not yet flown and to predict the speed of flutter onset. The analytical considerations leading to the technique are developed, followed by experimental evidence substantiating this approach.

Nomenclature

$a_{1,2,3}$ = coefficients arising in equation for lift forces, Eq. (A3)
$A_{0,1,2,3}$ = coefficients of characteristic equation
$b_{1,2,3}$ = coefficients arising in equation for aerodynamic moment, Eq. (A3)
$B_{0,1,2}$ = coefficients in prediction equation
$C_{L\alpha}$ = lift curve slope
f = flutter (subscript)
F = flutter margin
h = translational displacement of center of gravity, Fig. 3
I_c = moment of inertia of airfoil about center of gravity
k_α = torsion spring constant
k_h = bending spring constant
L = aerodynamic lift
m = mass of airfoil
M_c = aerodynamic moment referred to center of gravity
P = operator, d/dt
q = dynamic pressure = $\frac{1}{2}\rho V^2$
s = complex root of characteristic equation
V = velocity (airspeed)
x = distance of center of gravity aft of elastic axis
α = torsional displacement of airfoil
β = real part of solution of characteristic equation i.e., negative of decay rate
ω = imaginary part of solution of characteristic equation, i.e., frequency

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* Scientist. Associate Fellow Member AIAA.
† Senior Dynamics Engineer. Member AIAA.

Introduction

Background

THOSE who have been involved in flight flutter test programs are well aware of its hazardous nature and the difficulties of obtaining meaningful data. The damping vs velocity technique that is commonly employed presents definite hazards, such as the decision to proceed to higher speeds based on extrapolating the data obtained up to the last test speed. Uncertainties connected with the technique of extrapolation are further compounded by scatter in the measured damping data upon which the extrapolation is based, even if due care is exercised. Extreme dangers are particularly inherent for configurations prone to sudden and violent flutter, i.e., abrupt damping degradation with no prior warning.

These observations are shown more dramatically in Fig. 1 where velocity-damping trends are shown for three different