Improving the Quality of Motion Reproduction in Moving-Base, Piloted Flight Simulators

GEORGE R. MILLS*
Northrop Corporation, Hawthorne, Calif.

Motion reproduction is examined from the view point of the design and operation of the simulator motion control systems. Quality is chosen in the context of dynamic fidelity, the elimination of spurious small abrupt discontinuities in the acceleration response, and the attenuation of unwanted dynamic modes which reflect characteristics of the simulator structure. The techniques discussed have been recently applied, and experimental evaluations are presented. Motion servos which have been synthesized to accept voltage commands constructed from higher motion derivatives are shown to offer significant improvements in the fidelity of motion reproduction. The technique relies on the availability of higher derivative command signals, as voltage analogs in the typical analog simulation of the aircraft motion equations. A feedback technique is described which alleviates the problem of controlling simulator motions where control forces must be transmitted to the cockpit over a relatively compliant structure. The technique is implemented by bringing the coupling structure inside an acceleration feedback control loop. Applied to the control of vertical and lateral cockpit translations, the technique removes the most troublesome effects of simulator structural dynamics from the closed-loop motion response.

Nomenclature

θ = angular displacement of the beam about the pivoted end with respect to the ground reference, rad
Z = vertical translation of the cockpit with respect to ground reference. Straight-line motion and small-angle θ approximations are assumed, in.
T = output torque of servo applied about fixed beam pivot point, in.-lb
T_D = disturbance torque applied about fixed beam pivot point, in.-lb
e = drive voltage applied to input coil of the electrohydraulic servo valve, v
P_L = differential pressure between the active sides of the actuator pistons, psi
Q = total flow rate from the servo valve into the actuator ports, in.^{3}/sec
q_0 = flow rate which results in actuator motion, in.^{3}/sec
q_c = flow rate which results in fluid compression, in.^{3}/sec
q_L = flow rate which leaks past the actuator piston, in.^{3}/sec
t = independent time variable, sec
S = complex Laplace variable
$\mathcal{L}\{\ \}$ = Laplace transformation

System design parameters

M = equivalent cockpit mass (includes 2000 lb of gimbal weight) = 8.4 (lb-sec^2)/in.
I = beam inertia about beam rotation point = 2.4×10^5 in.-lb-sec^2
V_d = volumetric displacement of hydraulic drive = 1550 in.^{3}/rad
K = lumped structural stiffness of load = 6.60×10^3 lb/in.
C_p = linearized valve flow coefficient with respect to load pressure = 0.040 (in.^{3}/sec)/psi
C_ϵ = linearized valve flow coefficient with respect to input voltage = 250 (in.^{3}/sec)v
L = leakage coefficient of each actuator = 10^{-3} (in.^{3}/sec)/psi
N = bulk modulus of fluid = 2×10^5 psi
T_l = total stroke of actuator = 65 in.
r_1 = coupling radius of actuators = 73 in.
r_2 = coupling radius of cockpit = 235 in.
τ_v = valve time constant = 120^{-1} sec
K_0 = hydraulic spring rate = 11.6×10^8 (in.-lb)/rad
a = active actuator area = 21 in.^{2} (each cylinder)
V = trapped fluid volume/side (includes 134 in.^{3} of line volume) = 827 in.^{3} (midstroke)

Introduction

AN increasing number of ground-based flight simulation experiments are being flown which include requirements for simulating highly realistic motions of the cockpit. More recently, the trend in the requirements of these research experiments has been toward more complete motion simulation. The rigid-body aircraft motion response has been extended to include the higher-frequency flexible aircraft bending modes. Requirements for motion response to higher-frequency gust and air turbulence disturbance inputs have been added to the flying and maneuvering control inputs of the pilot. The equipment requirements of these programs has motivated the development of improved moving-base simulators which will accurately reproduce complex, large-amplitude, commanded motions with speed and smoothness. This paper discusses some of the principles relative to the operation of these simulator motion control systems and establishes techniques for the most effective use of available simulator motion capabilities.

An analytical design study of a large-amplitude, moving-base, five-degree-of-freedom flight simulator was conducted by the Research Laboratory of Northrop Norair during 1965.[1] The material presented here was primarily developed through these studies. The design criteria and techniques discussed have since been fully implemented in a new Northrop Norair large-amplitude flight simulator which became operational in June of 1966. Experimental verification of the analytical representations has therefore become available through actual experimental test and operation of the equipment.

A photograph of the Northrop simulator is shown in Fig. 1. Controlled rotations about axes at the base of the beam reproduce vertical and lateral translations of the cockpit; pitch, roll, and yaw cockpit rotations are reproduced by rotations of the gimbal system. The cockpit shown installed

---

Presented as Paper 67-252 at the AIAA Flight Test Simulation and Support Conference, Cocoa Beach, Fla., February 6–8, 1967; submitted February 17, 1967. Design studies were supported in part under contract AF33(615)2279, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio. Distribution of this document is unlimited. [10.06,12.09]

* Control System Design Specialist, Norair Division, Research Group.

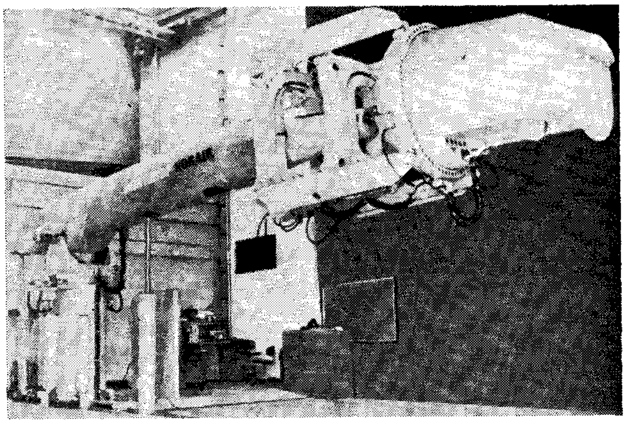

Fig. 1 Northrop large-amplitude simulator.

on the simulator has been dimensioned from drawings of a two-man aircraft. The cockpit weight, including the two-man crew, is 1250 lb.

The typical test situation, using moving-base flight simulators, involves the interaction of complex dynamic relationships between the pilot, his control system, a mathematical (usually analog) representation of the airplane response, a simulated visual display, and an amplitude-limited capability to supply high-response motion cues to the pilot. The interrelationship of these elements is shown by the block diagram on Fig. 2. The prime function of the motion control system is to reproduce simulator motions, at the pilot's station, in precise phase and amplitude correspondence to the electrical motion signals computed in the analog reference model. This control function also includes the cancellation or attenuation of motions that arise from structural bending modes which are characteristic of the simulator itself. In this respect, the motion control system is required to carry out a function usually identified with a model-following type of servo.

The reason for adding motion to the cockpit is to provide highly realistic kinesthetic cues for the pilot. As a consequence, the quality of the acceleration response in the motion, measured at the pilot's station, becomes the only significant basis for judging system merit. It is also clear that speed with smoothness, in the higher derivative acceleration wave forms, is most difficult to accurately reproduce.

The translational motion systems are required to precisely move the large translational inertia of the cockpit over large displacement amplitudes with speed and smoothness. The motion system design problem is therefore one of accurately controlling the motion of a large inertia load which is coupled to the servo-drive at the end of a heavy, long, and somewhat compliant structure.

A satisfactory level of fidelity in the output acceleration response must be simulated within limitations imposed by the following constraints:

1) Available control power imposes magnitude limits on acceleration and velocity motion response. Expressed in terms of sinusoidal motion, velocity saturation sets amplitude limits on output motion response over midrange frequencies and acceleration saturation determines motion amplitude limits in the high-frequency range.

2) Total travel of the simulator sets peak-to-peak displacement limits. Displacement limitations restrict motion amplitude capability in the low-frequency range.

3) The bandwidth of the motion control servo sets upper and lower limits on the dynamic response of the simulator.

4) An unavoidable level of nonlinear friction, i.e., coulomb friction and breakaway friction, exists in the output of the servo-drive.

Examples of the first three constraints, as expressed in terms of motion system performance, are specified graphically in Fig. 3. The motion performance is defined in terms of system response during steady sinusoidal motion, referenced at the pilot's station. The motion response of the Northrop large-amplitude simulator in vertical translation is used in the example.

In simulating aircraft motions, smoothness in the motion response is often of primary importance in a pilot's judgment of the motion quality. The smoothness characteristics of the motion are best obtained by monitoring the fidelity of the higher-derivative acceleration response of the simulator, at the pilot's station, with an accelerometer of good dynamic quality. Noise in its basic sense defines an abrupt change, often but not necessarily spurious and not periodic. Noise, in this sense, is the opposite of the smoothness characteristic desired. Nonlinear mechanical friction in the servo-drive is one of the most obvious detriments to smooth motion response. Other nonlinear characteristics which also contribute to this problem are small abrupt discontinuities about null in the system components, such as backlash or threshold-deadband, or poor smoothness qualities in the voltage output of primary motion feedback sensors themselves. For good quality motion reproduction, 0.1 g is a reasonable maximum upper limit for specifying over-all permissible abrupt or high-frequency distortion in the acceleration reproduction of the simulator.

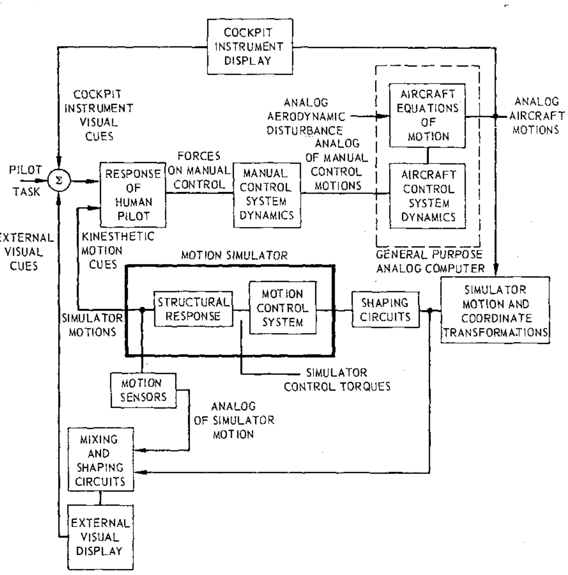

Fig. 2 Dynamic relationships in moving-base flight simulation.

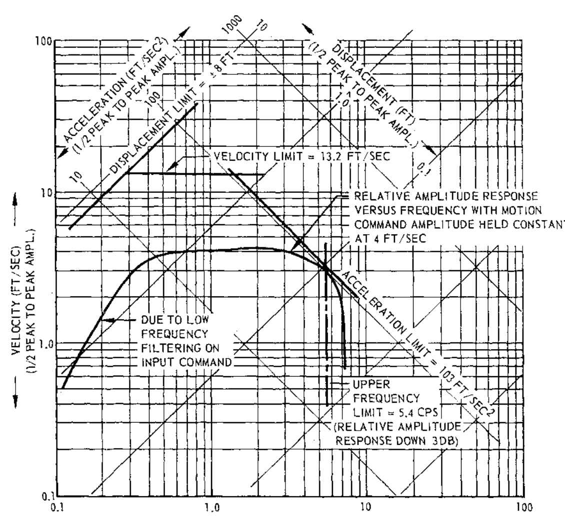

Fig. 3 Response of vertical translational motion system at the pilot's station to steady sinusoidal motion.

Theory and Implementation of Techniques

The careful selection of control system components to achieve the best possible performance with regard to the particular characteristics discussed previously is an obvious first requisite. Within this category are 1) a control power source that insures adequate saturation levels of acceleration and velocity, 2) the selection of transducers that minimize small discontinuous nonlinear effects and which have an adequate range of dynamic response, 3) output system mechanical elements that eliminate, insofar as possible, the effects of nonlinear friction in the drive, and 4) design criteria that insure the highest possible resonant frequencies in all structural elements which transmit drive power to the cockpit. With these criteria as a baseline, attention is now given to control techniques which most effectively use the available capacity for producing an output motion response of high quality.

The techniques developed are applicable to the general problem of reproducing high-quality motions. The hydraulically-controlled vertical translational motion servo of the Northrop large-amplitude simulator is used to implement the techniques in the discussions that follow.

Acceleration Feedback

The large-amplitude translational motion systems, in which the large inertia load of the cockpit is coupled to the servo-drive at the end of a heavy, long, and somewhat compliant structure, present two particularly difficult tradeoff problems to the control system designer:

1) A lightweight, highly efficient coupling structure is desirable in order to minimize the total inertia load which directly sets control power requirements and the over-all dynamic performance limits of the servos. On the other hand, a rigid coupling structure with sufficiently high structural resonances is necessary in order to provide a structure capable of transmitting the desired range of servo-drive frequencies without distorting the normal and lateral acceleration cues at the cockpit. Obviously, the correct choice between a highly efficient, lightweight, compliant structure and a rigid massive one is a compromise with respect to the frequency of the characteristic structural resonance.

2) The control power requirements of the systems controlling vertical and lateral translation of the cockpit when combined with the speed-of-response requirements compel the choice of fluid power for control. In a hydraulic system of this type, one of the limits on attainable servo bandwidth is related to the natural frequency established by the fluid compliance of the drive and the inertia of the load. Thus, for any fixed inertia, the characteristic actuator-load frequency can only be improved by increasing the physical size of the drive. Here again, particularly in the case of the servos that control the large translational inertia of the cockpit, practical consideration with regard to control power requirements, i.e., valve flow rates, actuator sizes, and fluid power sources, dictate a compromise with respect to the characteristic frequency of the actuator and load resonance.

The use of acceleration feedback compensation has been devised in answer to these two necessary compromises, with regard to the low-frequency structural or actuator-load resonances. This feedback compensation is effected by an acceleration-sensitive feedback-loop closure around the combined servo actuator and its elastic load. The result is an improvement in the apparent characteristics of the actuator-load dynamics, i.e., with respect to both natural frequency and damping ratio.

Emphasis in the discussion which follows is on the description of the technique successfully applied to the control of translational cockpit motion; unnecessarily complicated analytical representations of the structural and load dynamics have been avoided. A two-mass, lumped-parameter analytical model has been used. However, values assigned to the various structural and load parameters realistically reflect actual hardware characteristics.

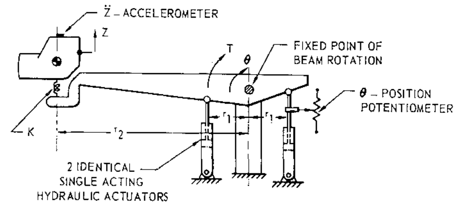

Fig. 4 Analytical model—vertical cockpit translation.

Figure 4 shows the analytical model representation. The control system design problem is written in terms of the variables in the Nomenclature. Using the notation of system design parameters (see Nomenclature) and the model of Fig. 4, the following relationships may be formed. Equation (2) represents the operation of a 4-way flow-control valve with constant (linearized) flow coefficients. Both single-acting cylinders are controlled by a single 4-way servo valve. Equation (6) is expressed with the actuator pistons at midstroke.

Hydraulic system equations

$$Q = q_0 + q_c + q_L \tag{1}$$

$$Q = [C_e e/(\tau_v S + 1)] - C_p P_L \tag{2}$$

$$q_0 = V_d S\theta = \mathfrak{L}\{V_d(d\theta/dt)\} \tag{3}$$

$$q_c = V_d^2 S P_L/K_0 = \mathfrak{L}\{(V_d^2/K_0)(dP_L/dt)\} \tag{4}$$

$$q_L = LP_L \tag{5}$$

$$K_0 = 2NV_d^2/V \tag{6}$$

$$T = V_d P_L \tag{7}$$

Mechanical/structural equations

The transmissibility of beam structure is

$$T_R = \frac{Z}{\theta} = \frac{r_2}{\left(\dfrac{S^2 + K/M}{K/M}\right)} = \frac{r_2}{\left(\dfrac{S^2 + \omega_1^2}{\omega_1^2}\right)} \tag{8}$$

where

$$\omega_1 = (K/M)^{1/2}$$

The driving-point mobility is

$$\mathfrak{M} = \frac{\theta S}{T} = \frac{\dfrac{1}{(I + r_2^2 M)}\left(\dfrac{S^2 + K/M}{K/M}\right)}{S\left[\dfrac{S^2 + \dfrac{K(I + r_2^2M)}{IM}}{\dfrac{K(I + r_2^2M)}{IM}}\right]} = \frac{\dfrac{1}{(I + r_2^2M)}\left(\dfrac{S^2 + \omega_1^2}{\omega_1^2}\right)}{S\left(\dfrac{S^2 + \omega_2^2}{\omega_2^2}\right)} \tag{9}$$

where

$$\omega_2 = [K(I + r_2^2M)/IM]^{1/2}$$

The foregoing set of equations is used to form the generalized block diagram of the system as shown on Fig. 5a. Position, velocity, and acceleration feedback control loops are shown. The acceleration feedback signal is shown measured at the cockpit, whereas the position and velocity signals are measured at the base end of the beam. This diagram is repeated in Fig. 5b with system parameters assigned.

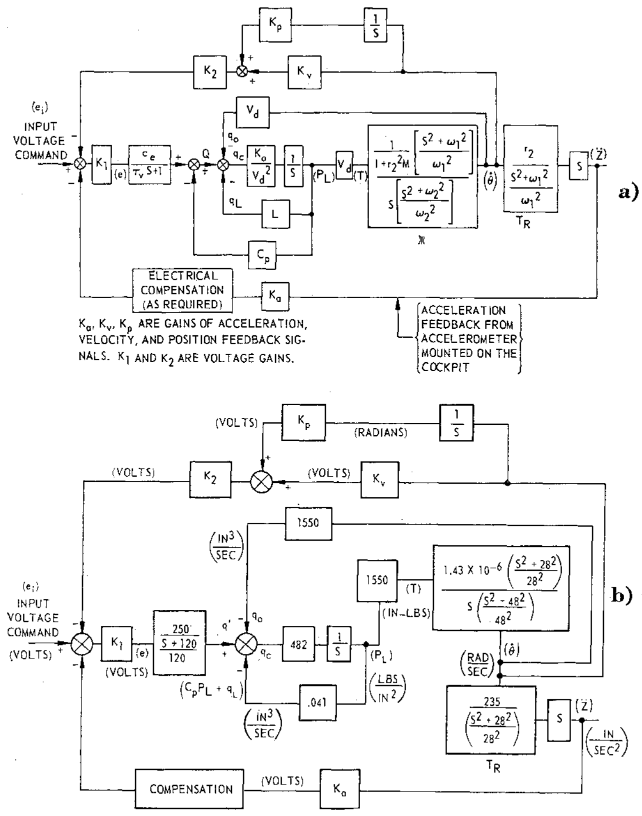

Fig. 5 Servo block diagram.

The blocks which express the valve, actuator, and load are solved using the root locus plot of Fig. 6. The resulting system block diagram is redrawn in Fig. 7. The difficult low-frequency lightly-damped structural-load resonance in the open-loop characteristic of the servo may now be explicitly identified in the transfer function of the combined valve, actuator, and load, i.e., at a natural frequency of 24 rad/sec and with a damping ratio of 0.12. It can be seen that a conventional position control loop closed around this open-loop characteristic offers no possibility of significantly modifying these lightly-damped low-frequency roots.

The root locus plot of Fig. 8, using acceleration feedback measured across the structural transmissibility, i.e., at the cockpit, shows clearly the effectiveness of this compensation technique. The low-frequency complex zeros which occur in the open-loop transfer function of the servo, due to the dynamics of the driving point mobility of the load, are exactly canceled by complex poles that appear in the acceleration signal due to the dynamics of the structural transmissibility. It then becomes readily possible to modify the root-locus of the low-frequency actuator/load resonance, a requirement which the inherent lead of the acceleration signal performs perfectly by providing a single zero at the origin. The compensation network in the acceleration feedback loop, not previously identified, has now also been mechanized to control the locus of the higher-frequency roots by incorporating a notch filter at 70 rad/sec.

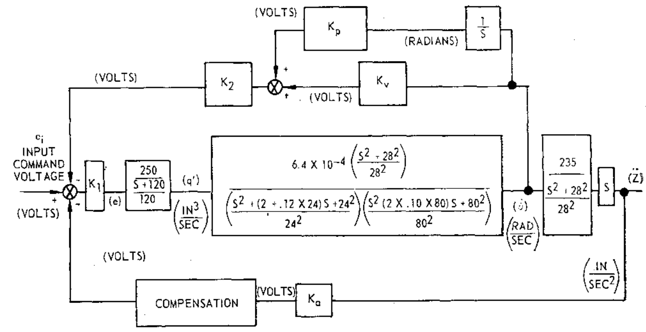

Fig. 7 Servo block diagram (valve, actuator, and load characteristics combined).

The acceleration feedback technique has achieved an output motion response free of low-frequency lightly-damped modes measured at the cockpit, within the following conditions: 1) a more lightweight, efficient structure, and 2) more readily realizable control power requirements. Design studies have also shown that similar results could have been achieved with an alternate technique based on feedback of actuator differential load-pressure. However, the use of pressure feedback introduces greatly increased compliance in the closed-loop characteristic of the servo. In this regard, pressure feedback effectively increases the magnitude of the valve flow coefficient with respect to load pressure, or with reference to Fig. 5a, the gain of the $C_p + L$ feedback loop. This added compliance, in turn, can only be offset by a corresponding increase in the sensitivity (or gain) of the position-sensitive feedback control loop. Investigations, as discussed in the next paragraphs, show that the lowest possible sensitivity levels of position-dependent signals

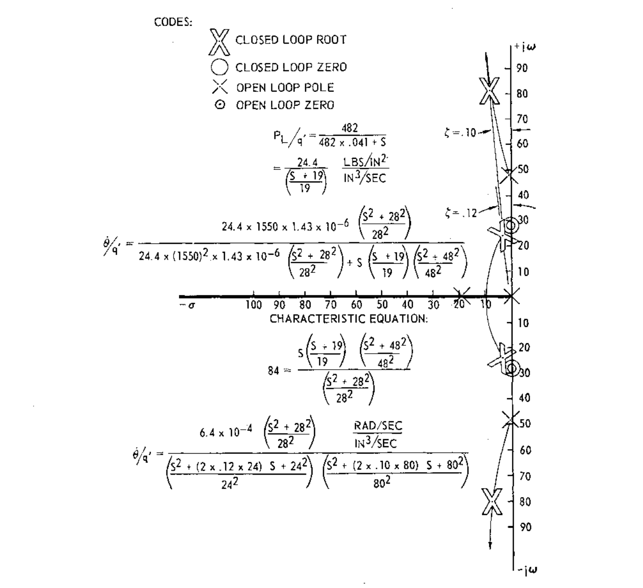

Fig. 6 Root-locus plot combining valve, actuator, and load characteristics.

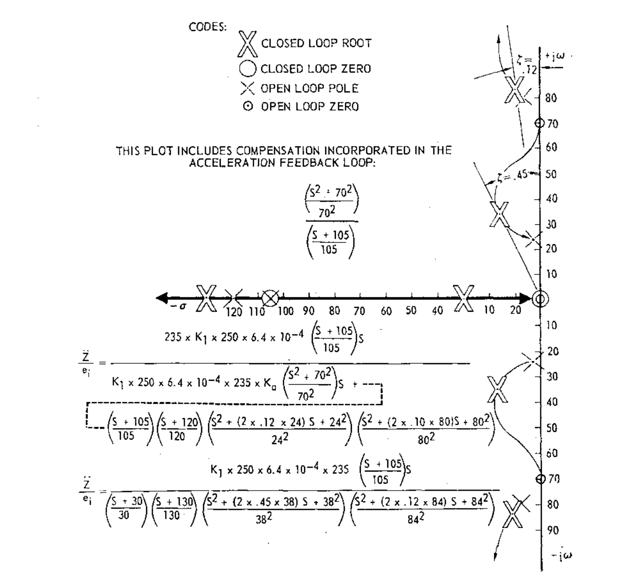

Fig. 8 Root-locus plot of acceleration feedback loop closure.

are of great importance with regard to the quality of smoothness in the output motion response. It is for this reason, i.e., to keep position feedback gains low and thereby to achieve the highest possible quality of smoothness in motion reproduction, that acceleration feedback compensation is considered far superior for this application than the more common pressure-feedback technique. A similar argument regarding the choice of pressure-control vs flow-control hydraulic servo valves also substantiates the use of flow-control valves in the synthesis of this type of simulator motion control system.

Input Command Using Higher-Derivative Analog Signals

This input drive technique achieves two very significant improvements in the quality of motion reproduction. 1) Series lead compensations can be readily incorporated in the input drive signal. By proper tuning, this lead compensation can be made to identically remove two (or more) lag terms in the closed-loop dynamic characteristics of the motion control servo. 2) By using the capability stated previously, an adequate range of dynamic response can be achieved without the necessity for a high-gain position-sensitive feedback control loop. The discussion below shows this feature to be an important factor with regard to smoothness in the motion response.

Requirements of high-response positional servos are reflected in large amplifications of feedback signals. Most problems related to qualities of smoothness in the motion response of postional servos can be traced to small abrupt discontinuities in position-dependent signals. Because of large open-loop gains, these abrupt discontinuities are readily amplified and reproduced in the position response of the servo. Any abrupt discontinuities in the position response obviously appear as spurious spikes in the time response of acceleration.

In conventional positional servo systems used in the motion control of large-amplitude flight simulators, attainable smoothness in motion reproduction is limited by these nonideal characteristics of the high-gain positional servo. The higher-derivative drive technique has been developed primarily in answer to this problem. The feasibility of the technique relies in the availability of higher-derivative command signals from the normal analog simulation of the aircraft equations. The mechanization depends on the use of high-gain velocity and acceleration feedback control loops in addition to the conventional position control loop.

A diagram illustrating the principle is shown in Fig. 9. The key issue of this approach lies in the dynamic response of the output motion vs each individual component of the input command. The positional control loop is synthesized with just sufficient open-loop gain to provide satisfactory stiffness to the servo. In the beam servos of the Northrop simulator, this stiffness requirement appears primarily due to the need for the beam servo to resist reaction loads generated by rotational motions of the cockpit servos. This value of open-loop gain in the position control loop of the servo automatically sets the level of dynamic authority between the position command signal and the output motion response. This range of authority for the position command signal has been determined to be from zero to approximately 0.2 cps. Small abrupt discontinuous transients in the position loop therefore have only slight capability to affect the output motion response.

The velocity control loops are synthesized to exercise primary motion control in the range of 0.2 to 3.0 cps. Transfer of control authority from the position command signal is accomplished by proper adjustment of position and velocity command signal levels in correspondence with the dynamic response of the position and velocity control loops. At approximately 3.0 cps, control authority is transferred from the velocity command signal to the acceleration command signal.

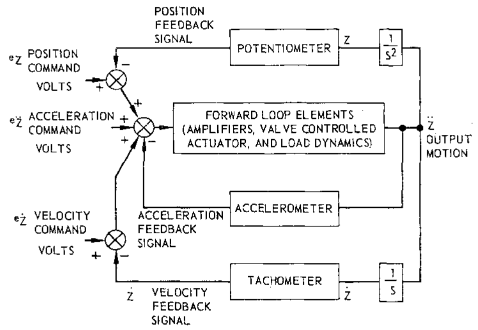

Fig. 9. Motion servo-drive technique.

In summary, the higher-derivative drive technique has achieved the following results: 1) a system which operates with the inherent smoothness of a velocity servo over the range of frequencies of most importance to the test requirements of moving-base simulation, i.e., from 0.2 to 3.0 cps, 2) sufficient position feedback to satisfy the servo stiffness requirements, and 3) a uniform motion response over a wider range of frequency, due to the opportunity available by the presence of higher-derivative input signals to mechanize lead compensations on the input electrical command to the motion servo.

Low-Frequency Input Filtering

The important motion cues in most moving-base simulation experiments come from the higher-frequency analog signals, i.e., above 0.1 cps, whereas it is the lower frequency motion signals which produce excessively large displacement excursions of the simulator. The raw signal inputs to the motion servos are translational and angular aircraft analogs of displacements, velocities, and accelerations as shown in the diagram of Fig. 2. Some type of low-frequency filtering of the input to the motion servos is obviously necessary in order to maintain the displacement excursions of the motion reproduction within the limits of the simulator motion envelope. Whether this is primarily a problem of displacement or velocity limitation can be judged by a diagram such as the one shown in Fig. 3.

A quantitative specification of the low-frequency attenuation required depends upon the particular simulation experiment being flown. The type of aircraft and the type of flight task directly affect this requirement. To a lesser degree, this dependency also extends to variations in the flying technique of different pilots. In any situation, the amplitude attentuation provided by the input filtering should be confined to the lowest possible frequency range. Available information on the phasing accuracy requirements in the motion response indicates that the phase angle should be minimized around 0.2 cps and above.

Low-frequency linear filters may be built into the system in several ways. One of the most convenient consists of using low-frequency lag circuits rather than perfect integrators for computing the velocity and position input drive signals from the acceleration analog signal.[2] This technique will provide a low-frequency rolloff at 12 db per octave. Additional d.c. blocking filters may be used to exclude low-frequency acceleration signals as required.

A method using a control loop, which feeds back the integral of simulator position (from null) to provide a nonlinear type of low-frequency filtering, is diagrammed in Fig. 10. This technique has been developed primarily for use in washing out sustained large-amplitude vertical accelerations which occur in steady longitudinal maneuvers. The zener diodes in the circuit break down successively as the simulator approaches the vertical displacement limits. The result achieves a progressive increase in the low-frequency washout as the simulator moves toward the travel stops.

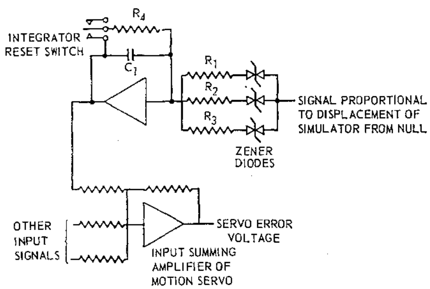

Fig. 10 Diagram of nonlinear low-frequency filtering technique.

Demonstration of Results

The techniques discussed have been used in the motion servos that reproduce vertical and lateral translation of the cockpit in the Northrop large-amplitude simulator. An experimental verification of the over-all dynamic response of these systems is shown by the frequency vs amplitude ratio plots of Fig. 11. These response plots relate the vertical motion computed at the pilot's station in the analog aircraft to the actual motion measured by a high-quality accelerometer mounted at the pilot's station in the simulator. The particular motion may be considered either position, velocity, or acceleration, i.e., position command to position response or velocity command to velocity response, provided all required motion derivatives are present in composite command signal. The low-frequency filtering evident in these response plots was adjusted for a particular longitudinal control task.

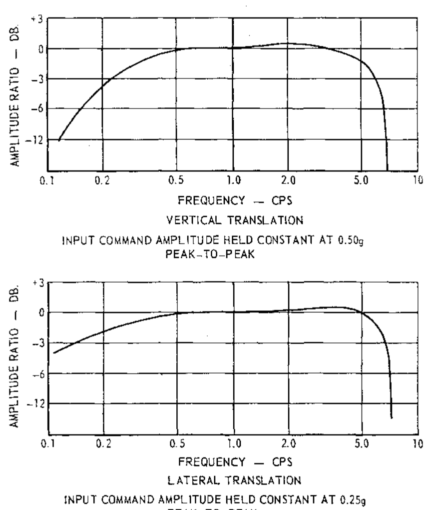

Fig. 11 Beam servo dynamic response

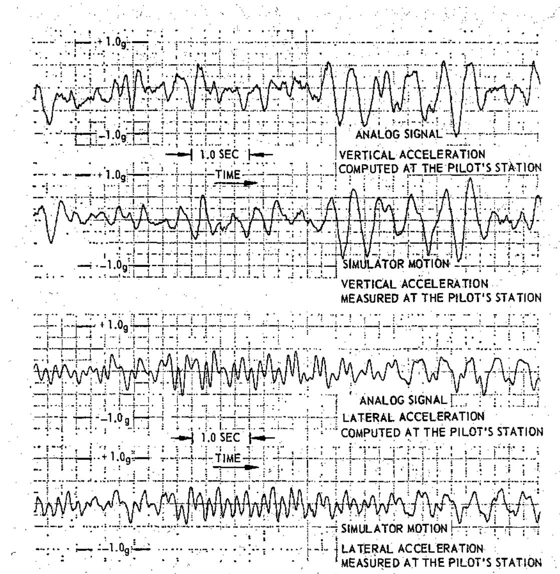

Fig. 12 Reproduction of translational cockpit motion (moderate-to-heavy turbulence).

Figure 12 shows recordings taken during a simulation flight in which normal acceleration computed by the analog at the pilot's station is compared with the corresponding motion measured by a high-quality accelerometer located under the pilot's seat in the simulator cockpit. The large flexible aircraft being simulated includes several longitudinal bending modes, and the aircraft is flying in moderate-to-heavy turbulence. Figure 12 also shows similar recordings in the lateral plane. The excellent reproduction of a lightly-damped lateral bending mode in the aircraft at approximately 6.5 cps is clearly evident in the traces.

A total payload weight, i.e., cockpit plus two crewmen, of approximately 1250 lb was carried by the simulator during the response measurements shown.

References

[1] Cooles, H. D., Mills, G. R., and Patton, D. L., "Advanced dynamic aeronautical simulator design study," Northrop Corp., Norair Div., Rept. NOR-65-280 (October 1965).

[2] Robertson, D. I., Brenchly, N., and Rumsey, P. C., "A moving cockpit flight simulator with five degrees of freedom," British Aircraft Corp. Ltd., Paper 142.