Comparison of Ground-Based and In-Flight Simulation of VTOL Hover Control Concepts

Lloyd Corliss*
NASA Ames Research Center, and Aeromechanics Lab., U.S. Army Aviation R&D Command, Moffett Field, Calif.

and

Richard K. Greif* and Ronald M. Gerdes†
NASA Ames Research Center, Moffett Field, Calif.

Results of several parametric ground-based simulations covering a variety of VTOL in-hover control concepts are reviewed. The systems considered are angular acceleration, rate, and attitude control, as well as translational rate control. Since many cues are severely restricted by ground-based simulation (e.g., motion, peripheral vision, and environment), some form of in-flight validation of these results is desired. Such a study has been undertaken utilizing the NASA Ames X-14B VTOL aircraft. This in-flight simulator has been configured with a fly-by-wire capability in the hover mode through an analog/digital variable stability system. This system permits the implementation of either response-feedback or model-following type of control. A comparison of flight and ground-based data is shown for the attitude control system, with the X-14B being flown in both a tethered hover and a free-flight hover.

Nomenclature

g	= gravitational constant, f/s^2 (m/s^2)
I_x, I_y, I_z	= aircraft moments of inertia about x_b, y_b, z_b, slug-ft^2 (kg-m^2)
K_{v_x}, K_{v_y}	= longitudinal and lateral velocity stabilization, rad/s^2/f/s (rad/s^2/m/s)
K_δ	= stick sensitivity gain, rad/s^2/cm
$K_{\delta_\theta}, K_{\delta_\phi}$	= pitch and roll stick sensitivity, rad/s^2/cm
K_θ, K_ϕ	= pitch and roll attitude stabilization, rad/s^2/rad
$K_{\dot\theta}, K_{\dot\phi}$	= pitch and roll rate stabilization, rad/s^2/rad/s
K_1, K_2	= cubic polynomial coefficients
$L_{(\ )}/I_x$	= rolling acceleration due to ( ), rad/s^2/( )
$M_{(\ )}/I_y$	= pitching acceleration due to ( ), rad/s^2/( )
V_x, V_y	= linear velocities along x and y, f/s (m/s)
x, y, z	= inertial axes
x_b, y_b, z_b	= aircraft body axes
$\delta_\theta, \delta_\phi$	= pitch and roll control input, cm
θ, ϕ	= pitch and roll Euler angles, rad
θ_c, ϕ_c	= pitch and roll commands, rad
ζ	= damping ratio
ω_n	= natural frequency, 1/s

Subscript

ss	= steady-state value

Superscript

$'$	= augmentation terms

Acronyms

PR	= pilot rating (Cooper-Harper)
TR	= translational rate
CP	= control power, rad/s^2
SCAS	= stability and control augmentation system

Presented as Paper 77-610 at the AIAA/NASA-Ames V/STOL Conference, Palo Alto, Calif., June 6-8, 1977; submitted June 6, 1977; revision received Nov. 28, 1977. Copyright© American Institute of Aeronautics and Astronautics, Inc., 1977. All rights reserved.

Index categories: Handling Qualities, Stability and Control; Simulation.

*Aerospace Engineer.

†Aerospace Engineer and Pilot.

Introduction

THE attributes and, in some cases, the requirement for augmentation of the inherent flight control characteristics of most VTOL aircraft in hover are well recognized. Many VTOL types exhibit a nearly acceleration response to a control input. For a VTOL whose X-Y displacements are achieved largely through angular change (i.e., roll, pitch, and yaw) rather than linear change (i.e., thrust vectoring), a variety of levels of augmentation exists.

Figure 1 depicts four increasingly complex levels of roll axis augmentation providing command systems of either angular acceleration (all switches open), angular rate, attitude, or translational rate (all switches closed). It is assumed that any inherent stabilization of the vehicle (e.g., L_p/I_x and L_v/I_x) can be lumped into the K gain terms, and also that the small angle approximation of $\dot V_y \simeq g\phi$ is valid. A similar hierarchy of control in hover exists for the pitch axis. Various aspects of these levels of control have been the point of several ground-based simulation studies.

This paper presents a summary of two of those ground-based studies and a comparison between ground and flight results for a parametric evaluation of the attitude command system utilizing the X-14B VTOL in-flight simulator.

Review of Ground Simulator Results

Contained in Refs. 1 and 2 is a combined study of several levels of control for the pitch and roll axes utilizing the same ground simulator facility. Reference 1 presents a parametric simulation study for pitch and roll of the acceleration, rate,

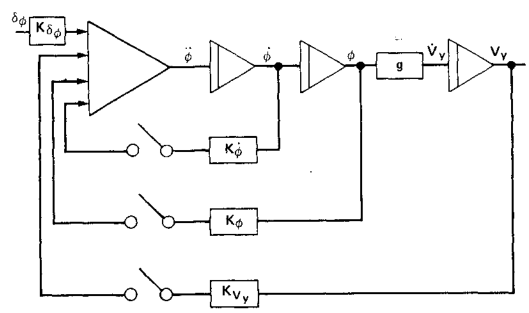

Fig. 1 Levels of stabilization (roll axis).

Table 1 Hover control equations

Control type	Pitch axis		Roll axis	
Acceleration	$\delta_\theta K_{\delta_\theta}$	$=\ddot{\theta}$	$\delta_\phi K_{\delta_\phi}$	$=\ddot{\phi}$
Rate	$\delta_\theta K_{\delta_\theta}$	$=(S+K_{\dot{\theta}})\dot{\theta}$	$\delta_\phi K_{\delta_\phi}$	$=(S+K_{\dot{\phi}})\dot{\phi}$
Attitude	$\delta_\theta K_{\delta_\theta}$	$=(S^2+K_{\dot{\theta}}S+K_\theta)\theta$	$\delta_\phi K_{\delta_\phi}$	$=(S^2+K_{\dot{\phi}}S+K_\phi)\phi$
		$=(S^2+2\zeta\omega_n S+\omega_n^2)\theta$		$=(S^2+2\zeta\omega_n S+\omega_n^2)\phi$
Translation rate	$\delta_\theta g K_{\delta_\theta}$	$=(S^3+K_{\dot{\theta}}S^2+K_\theta S-gK_{v_x})V_x$	$\delta_\phi g K_{\delta_\phi}$	$=(S^3+K_{\dot{\phi}}S^2+K_\phi S+gK_{v_y})V_y$
		$=(S^2+K_I\omega_n S^2+K_2\omega^2{}_n S+\omega_n^3)V_x$		$=(S^3+K_I\omega_n S^2+K_2\omega_n^2 S+\omega_n^3)V_y$

and attitude systems, and Ref. 2 includes the translational rate system. The character of each of these systems is described by the equations shown in Table 1. The rationale for the equations in the table and how they may be related to an augmented vehicle in hover are briefly described below.

Consider first the translational rate system for the roll axis, as given in Table 1. This control equation can be constructed by starting with a basic decoupled hover equation for roll, given in Ref. 3:

$$\frac{L_\delta}{I_x}\delta_\phi = S\left(S-\frac{L_p}{I_x}\right)\phi-\frac{L_v}{I_x}V_y \tag{1}$$

By augmenting the vehicle (e.g., with a SCAS) with the terms K'_{δ_ϕ}, $K'_{\dot{\phi}}$, K'_ϕ, and K'_{v_y}, this equation becomes

$$K'_{\delta_\phi}\frac{L_\delta}{I_x}\delta_\phi=\left[S^2+\left(K'_{\dot{\phi}}-\frac{L_p}{I_x}\right)S+K'_\phi\right]\phi+\left(K'_{v_y}-\frac{L_v}{I_x}\right)V_y \tag{2}$$

Then, by grouping the inherent and the augmenting terms into total stabilization terms [e.g., $K_{\dot{\phi}}=K'_{\dot{\phi}}-(L_p/I_x)$, etc.], and by using the small angle approximation $\dot{V}_y=g\sin\phi\simeq g\phi$, Eq. (2) yields

$$gK_{\delta_\phi}\delta_\phi=(S^3+K_{\dot{\phi}}S^2+K_\phi S+gK_{v_y})V_y \tag{3}$$

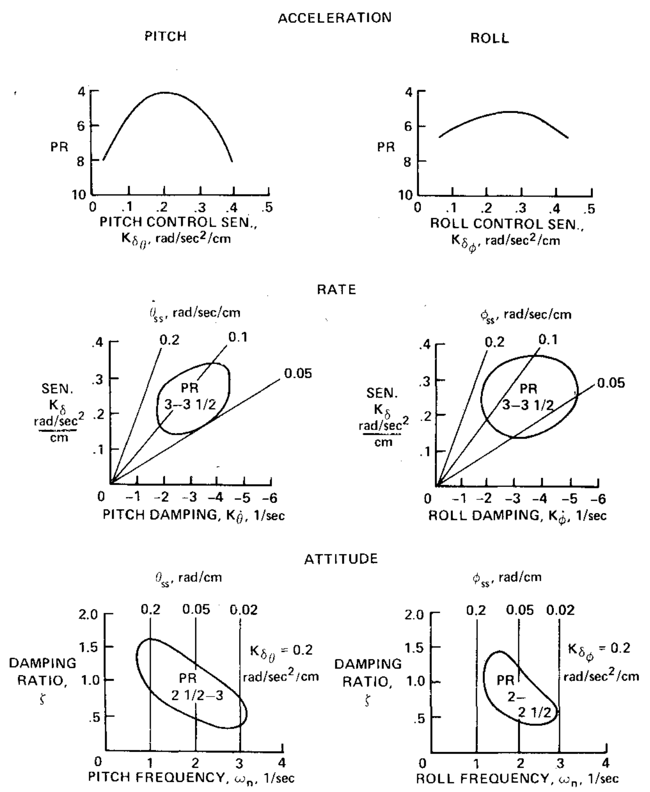

Fig. 2 Results of Ref. 1.

This equation is of the form given in Table 1 and is depicted in Fig. 1. By setting $K_{v_y}=0$, one can easily see the form of the attitude system and, similarly, with $K_{v_y}=K_\phi=0$, the angular rate system.

The simulation studies of Refs. 1 and 2 were conducted on the NASA Ames six-degree-of-freedom simulator. These studies considered an open cab, real world VFR task in hover with 1:1 scale motion within the simulator confines of a 5.5-m cube. Parametric studies to determine the optimum values of control sensitivity, damping, and stiffness were made using the Cooper-Harper pilot rating (PR)[4] as the primary criterion. Results from Ref. 1 for the acceleration, rate, and attitude systems are shown in Fig. 2.

Results for the translational rate system were obtained from Ref. 2, and are elaborated on briefly below. This system, as given by the equation of Table 1, has four variables for consideration: K_δ, K_I, K_2, and ω_n. The variables K_I and K_2 have mainly a damping effect on the dynamic response of this equation. Several classes of filter forms which conform to this equation format aided in the selection of K_I and K_2. For the simulation of Ref. 2, two such filter forms, the Butterworth (where $K_I=K_2=2$) and the binomial (where $K_I=K_2=3$) were considered as representative of the damping characteristic of most interest. The former, which has a factored form of $(S+\omega_n)[S^2+2(0.5)\omega_n S+\omega_n^2]$, exhibits a step response similar to a second-order, mildly damped ($\zeta=0.5$) response; while the latter, with a factored form of $(S+\omega_n)^3$, is similar to a critically damped ($\zeta=1.0$) response. When comparing these two forms for several choices of ω_n and K_δ, a piloted simulation revealed a definite preference for the critically damped response of the binomial form. With this preference for a well-damped response, K_I and K_2 were held constant at 3, and the remainder of the simulation centered on parametric variations in the sensitivity K_δ and the natural frequency of the cubic equation ω_n. The results of this study, as given in Ref. 2, are shown in Fig. 3. These results are for a hovering

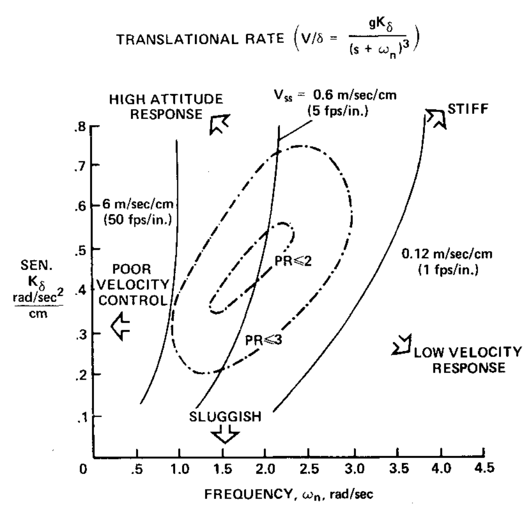

Fig. 3 Optimum TR system for pitch and roll.

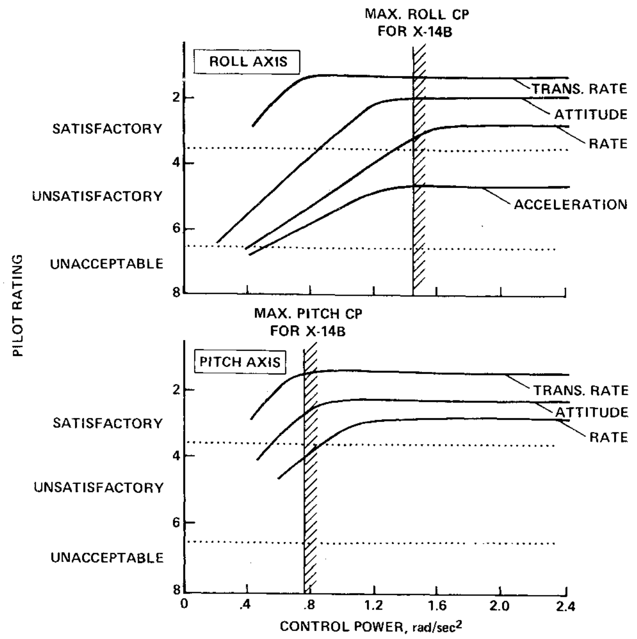

Fig. 4 A comparison of ground-based simulator results.

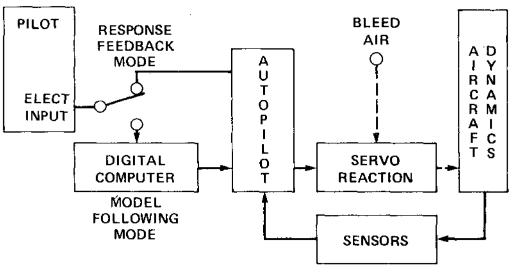

Fig. 5 X-14B system block diagram.

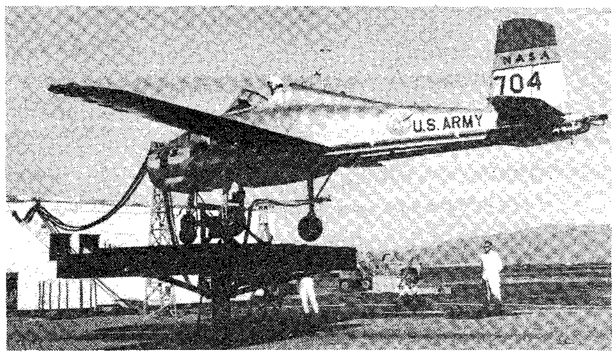

Fig. 6 X-14B in tethered flight.

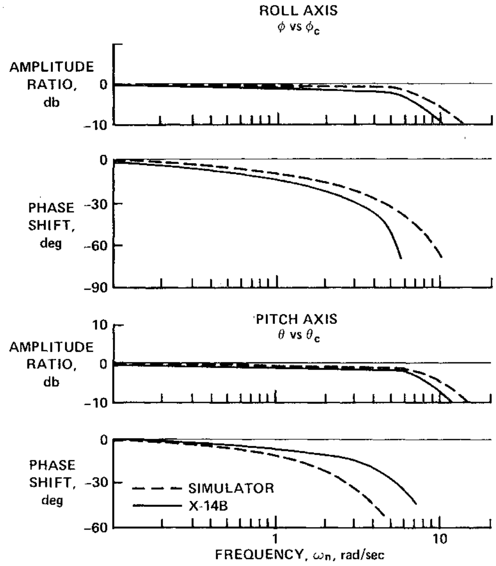

Fig. 7 Simulator vs X-14B aircraft.

VFR task of rapid maneuvering and stationkeeping for which the roll and pitch control characteristics were varied together.

One final outgrowth of Refs. 1 and 2 is a comparison of the optimized versions of all four modes of control, based on pilot rating vs available control power, as shown in Fig. 4. These results indicate a hierarchy of control in hover for four modes of control of the pitch and roll axes. These plots also show that the attitude and translation rate systems require less control power for satisfactory ratings. The penalties for improved control characteristics are, of course, added cost and the complexity of additional sensors and feedback logic. Thus, as always, the designer is faced with the tradeoff of minimizing the complexity yet maximizing the capability. In many cases, the choice of control augmentation is likely to center around the angular rate or attitude-type control system as the best compromise.

As indicated earlier, some form of in-flight verification of these ground-based results is desirable. The X-14B in-flight simulator was used to conduct this in-flight verification.

X-14B In-Flight Simulator

The NASA Ames X-14B is a jet-lift VTOL which has been flown for 20 years and used extensively in various programs. The most recent modification to this vehicle includes the addition of an analog/digital, variable-stability system with servoed reaction control nozzles. The nozzles, which are supplied by engine bleed air, provide roll, pitch, and yaw control in hover. A block diagram showing this system is given in Fig. 5, and a more detailed description of the system is contained in Refs. 5 and 6. The present configuration provides a fly-by-wire capability in the hover mode, which allows for in-flight simulation using either a response feedback mode or a model-following mode of control.

The model-following type of control on the X-14B was considered the primary mode of operation for comparing the referenced simulator results to flight. This mode of control best minimizes the effects of disturbances and cross coupling, and thus best duplicates the characteristics of the ground simulator, which was also operated as a model follower. The validity of such a comparison depends, in part, upon how well the frequency response of the X-14B model-following system compares with that of the simulator. To this end, the X-14B was operated under full power on a tethered test stand (Fig. 6) and driven in the model-following mode at frequencies from 0.1 to 1 Hz. Figure 7 shows these results in comparison with the pitch and roll amplitude/phase plots of the six-degree-of-freedom simulator. The two systems compare favorably and have adequate bandwidth for investigating systems in the frequency range of interest (i.e., $\omega_n = 1\text{-}3$ rad/s).

Another very important consideration in such a comparative study of flight vs simulator results is the matter of control power. The control schemes of Ref. 1 were optimized on the simulator at control power levels high enough (around 2 rad/s^2 in both roll and pitch) to minimize the probability of their influence. The optimized systems were then compared at various levels of control power, as already shown in Fig. 4. This figure also shows the maximum levels of control power available in the X-14B (1.4 rad/s^2 in roll and 0.75 rad/s^2 in pitch). It should be noted that the control powers of the X-14B are in a region where the simulator shows that pilot rating has a dependency on control power. This dependency is less pronounced in the X-14B roll axis than in the pitch axis but, in either case, it is a factor to be considered when comparing the data.

Test and Results

The stabilization system, first considered for in-flight simulation on the X-14B, was an attitude control system in pitch and roll. The initial phases of this simulation included "flying" on a test stand in a tethered hover mode (Fig. 6), followed by a free-flight mode at an altitude of about 800 m. These modes were necessary from an operational standpoint for the safety they provided during the system-check stage. The same pilot who had participated extensively in the ground simulation was the test pilot for the in-flight simulation. Data were taken for the same attitude system characteristics as considered in Ref. 1, with the X-14B operating in both the response-feedback and model-following modes. Comparisons of these results are shown below.

Simulator vs Free Flight

The primary purpose of this study was a comparison of free-flight results vs simulator results for a variety of attitude system characteristics. This comparison for the pitch and roll axes is shown in Fig. 8. The X-14B was operated in the model-following mode, and variations in pitch and roll were made separately. The control sensitivities in both axes were held constant at 0.18 rad/s^2/cm. A sweep of control sensitivity in flight showed this value to be preferred, and is a value which correlates well with the results of Ref. 1. The dashed line contours of Fig. 8 represent the results of the ground-based simulation as discussed in Fig. 2; the solid line contours represent in-flight simulation results. In both cases, the closed contours include systems with up to ½ PR better than the values shown. In general, there is a reasonable correlation of flight to ground-based results; however, the flight data for both pitch and roll do indicate the pilot was more tolerant of a wider frequency range and less tolerant of low damping. It should be emphasized that the free-flight data were taken at an altitude of 800 m and, while the pilot had good angular cues, his visual linear cues were at best marginal. This certainly hindered the precision with which the pilot could position the vehicle and likely influenced his acceptance of a wider band of frequencies.

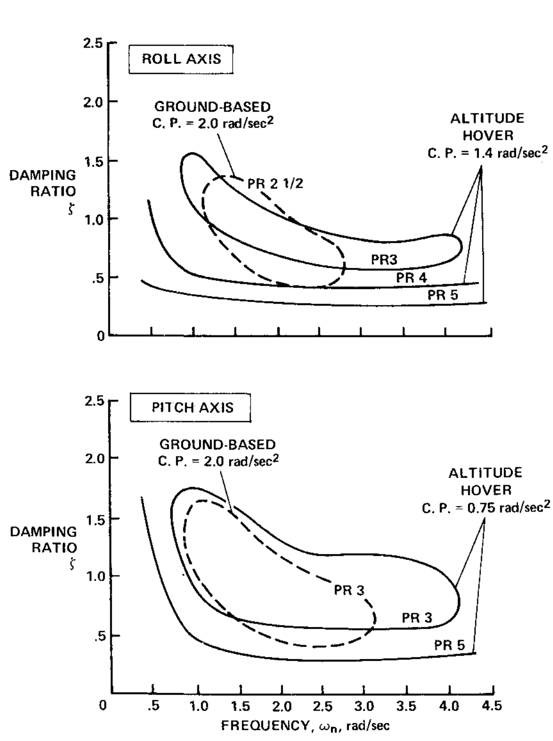

Fig. 8 Ground-based vs free flight (model-following mode).

Model Following vs Response Feedback

Shown in Fig. 9 is a comparison of the pitch attitude control system in free flight as implemented by a response-freedback method vs model-following method. Also superimposed on this figure are the ground simulator results. As can be seen, the gain limits of the X-14B response-feedback mode did not permit the simulation of the complete region of interest. However, for the area that could be investigated, the response-feedback results very closely agreed with the simulator results and fell largely within the bounds of the model-following results. It should be noted that the response-feedback results showed a degradation in pilot rating (PR = 3½) over either the model-following results (PR = 3) or the simulator results (PR = 3). This correlates with the general preference the pilot had for the model-following mode over the response-feedback mode of operation in flight. The sensation felt by the pilot with model-following type control was that of a "locking-on" effect when engaging that mode. This was described as similar in effect to the caging of a gyro, and resulted in a less disturbed response while operating in the model mode. The sensation, which did not occur with the response-feedback mode, is consistent with the expected benefits of model following for minimizing effects due to disturbances and other aircraft variations. Although the preference for the model-following type of control was pronounced, a more concentrated comparison of the two types of control with known and repeatable disturbances would be desirable. It should be noted that model-following control is not achieved without the cost of added complexity to the control system. No attempt will be made here to address such tradeoffs, but rather to provide a brief comparison from the pilot's view of the two control schemes.

Free Flight vs Tethered Flight

Prior to the free-flight hover tests with the X-14B, the candidate attitude systems were tested with the aircraft

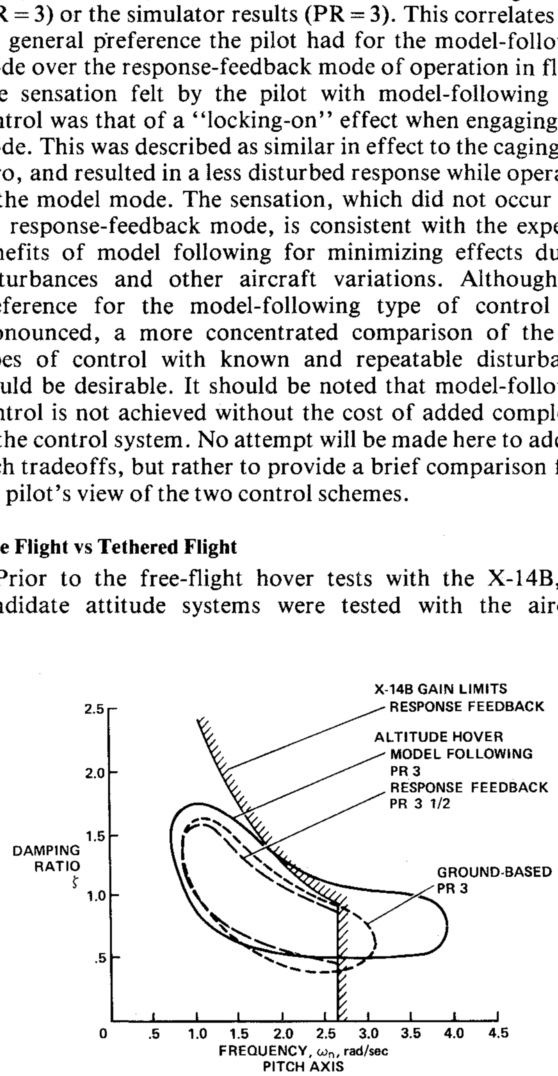

Fig. 9 Model following vs response feedback (pitch attitude system).

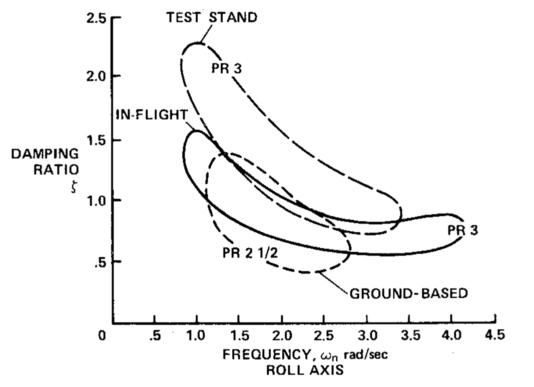

Fig. 10 Model mode (roll axis attitude system).

operating under power on a test stand, as shown in Fig. 6. This test stand secured the X-14B through a ball and socket near the center of gravity, allowing for travels of approximately 30 cm in z, ± 10 deg in pitch and roll, and ± 6 deg in yaw. The vehicle was restrained in x and y. A more complete description of the test stand can be found in Ref. 6. The procedure for operating in this tethered mode was to lift off to the upper stop of the restraint and to make mild steps and control reversals in the axis under investigation. This mode of operation thus limited the travel to the three angular degrees of freedom. The results for the roll axis attitude system comparing tethered flight vs free flight are shown in Fig. 10. Also superimposed on this figure are the ground simulator results of Ref. 1. These results show a greater discrepancy between the tethered data and the simulator data than the free-flight and simulator data. The tethered data generally favored a much higher damping characteristic. A similar trend was noted for the pitch axis. The contributing factors for these differences are probably the limited motion of the tethered mode and the fact that this mode had three degrees of freedom, while the simulator and free-flight modes had six degrees of freedom.

Conclusions

This paper presents a review of two ground-based simulation studies of VTOL in-hover control concepts and describes a comparative in-flight simulation of one of those concepts. The concept considered was an attitude-stabilized system. The results with the X-14B VTOL in-flight simulator showed a good correlation of free-flight data with ground simulator data. Additional data from this study showed a comparison between a model-following type of control and a response-feedback type of control. This phase of the study indicated a degradation in pilot rating with the response-feedback method vs the model-following method for the same attitude system characteristics. While this is consistent with expected results, a more controlled comparison of these two types of control schemes would be desirable. A comparison of free flight vs tethered flight of the X-14B revealed a shift in desired attitude characteristics. These data indicated that while the test stand is a useful device for system checkout, its limited motion and restraint of the linear degrees of freedom affected a significant variation in the desired attitude characteristics over those determined in either free flight or with the ground simulator.

References

[1] Greif, R.K., Fry, E.B., Gerdes, R.M., and Gossett, T.D., "Effects of Stabilization on VTOL Aircraft in Hovering Flight," NASA TN D-6900, Aug. 1972.

[2] Corliss, L.D. and Dugan, D.C., "A VTOL Translational Rate Control System Study on a Six-Degree-of-Freedom Motion Simulator," NASA TM X-62,194, Oct. 1972.

[3] Wolkovitch, J. and Walton, R.P., "VTOL and Helicopter Approximate Transfer Functions and Closed-Loop Handling Qualities," Rept. STI-TR-128-1, Systems Technology, Inc., Hawthorne, Calif., June 1965.

[4] Cooper, G.E., and Harper, R.P., Jr. "The Use of Pilot Ratings in the Evaluation of Aircraft Handling Qualities," NASA TN D-5153, 1967.

[5] Gallagher, J.T., Saworotnow, I., Seeman, R., and Gossett, T.D., "A Model Following Variable Stability System for the NASA ARC X-14B," *Journal of Aircraft*, Vol. 9, July 1972, pp. 461-469.

[6] Pauli, F.A., Corliss, L.D., Selan, S.D., Gerdes, R.M., and Gossett, T.D., "The Use of an Aircraft Test Stand for VTOL Handling Qualities Studies," NASA TM X-62,218, June 1974.

From the AIAA Progress in Astronautics and Aeronautics Series . . .

SPACE-BASED MANUFACTURING FROM NONTERRESTRIAL MATERIALS-v. 57

Editor: Gerard K. O'Neill; Assistant Editor: Brian O'Leary

Ever since the birth of the space age a short two decades ago, one bold concept after another has emerged, reached full development, and gone into practical application—earth satellites for communications, manned rocket voyages to the moon, exploration rockets launched to the far reaches of the solar system, and soon, the Space Shuttle, the key element of a routine space transportation system that will make near-earth space a familiar domain for man's many projects. It seems now that mankind may be ready for another bold concept, the establishment of permanent inhabited space colonies held in position by the forces of the earth, moon, and sun. Some of the most important engineering problems are dealt with in this book in a series of papers derived from a NASA-sponsored study organized by Prof. Gerard K. O'Neill: how to gather material resources from the nearby moon or even from nearby asteroids, how to convert the materials chemically and physically to useful forms, how to construct such gigantic space structures, and necessarily, how to plan and finance so vast a program. It will surely require much more study and much more detailed engineering analysis before the full potential of the idea of permanent space colonies, including space-based manufacturing facilities, can be assessed. This book constitutes a pioneer foray into the subject and should be valuable to those who wish to participate in the serious examination of the proposal.

192 pp., 6 × 9, illus., $15.00 Mem., $23.00 List

TO ORDER WRITE: Publications Dept., AIAA, 1290 Avenue of the Americas, New York, N. Y. 10019