A Hover Augmentation System for Helicopters

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Although the ability to hover at a fixed point in space is one of the unique advantages of the helicopter over fixed-wing aircraft, it is achieved accurately only with a great deal of pilot attention and effort because four integrations occur between the pilot's input and the resulting displacement of the aircraft. By means of feedback proportional to the helicopter's translation and its derivatives, the hover augmentation system (HAS) reduces the pilot effort required to hover the helicopter or to maneuver from one point to another at nearly zero speed, and to permit these maneuvers to be achieved with greater accuracy. Implementation of the HAS is achieved by the use of automatic pilot sensors and a special purpose analog computer to perform the axis conversion from an aircraft-axis system to an earth-reference system. Addition of the HAS to a helicopter equipped with a stability augmentation system (SAS) allows the helicopter to be hovered at a point in space with a resulting reduction of the integral square error by an order of magnitude when compared to the SAS-equipped helicopter alone. The pilot task is reduced from one requiring full-time attention with the SAS alone to one requiring only sporadic attention when the HAS is used.

Nomenclature

AFCS = automatic flight control system
CAS = command augmentation system
HAS = hover augmentation system
ISA = integral squared activity
ISE = integral squared error
OLCS = outer loop control system
SAS = stability augmentation system
u = body axis longitudinal velocity + forward
v = body axis lateral velocity + right
w = body axis vertical velocity + down
k = acceleration gain of HAS, in./fps^2
V_x = earth referenced longitudinal velocity + forward
V_y = earth referenced lateral velocity + right
V_z = earth referenced vertical velocity + down
X = longitudinal aircraft displacement + forward
Z = vertical aircraft displacement + down
α = ratio of velocity to acceleration gain in HAS
δ = cockpit control movement
δ_C = cockpit collective control movement
δ_L = cockpit longitudinal control movement
θ = aircraft pitch attitude
ϕ = aircraft roll attitude
ψ = aircraft yaw attitude
$(\dot{\ })$ = first derivative with respect to time
$(\ddot{\ })$ = second derivative with respect to time

Introduction

To utilize the capabilities of a helicopter, a portion of each flight is spent at hover. Accurate positioning at hover is difficult for the pilot to achieve unless augmentation of the helicopter handling qualities is provided. The hover augmentation system simplifies the pilot task by providing closed-loop control of the vehicle translational accelerations and velocities. Maneuvering capability is enhanced by modifying the pilot commands to approximate a velocity response to a control step.

Implementation of the HAS was achieved by the use of sensors of automatic pilot quality and by an axis-conversion computer fabricated from solid-state electronic circuits. This paper describes the design of the HAS, the engineering model of the equipment, and the performance verification studies performed with a helicopter control system simulator and an analog computer simulation of the helicopter and flight control system equations.

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Statement of the Problem

Most helicopter missions require portions of the flight to be conducted at hover. Typical hovering tasks are the handling of cargo sling loads, the rappeling of troops, and the placement of a dipping sonar in the ASW mission. In performing the latter task, the pilot is frequently required to fly a mission of up to 4 hr duration during which the aircraft may be brought to a hover as often as every 10 min. Performing this task places a large demand on the pilot's attention merely to control the helicopter, thereby diverting him from other duties whose performance may be critical to the success of the mission.

A better idea of the nature of the problem may be obtained from Fig. 1. This figure shows the time history of pilot inputs to the collective and cyclic pitch sticks of a simulated CH-47 helicopter while hovering in mild turbulence. These records, which were obtained from simulation studies whose

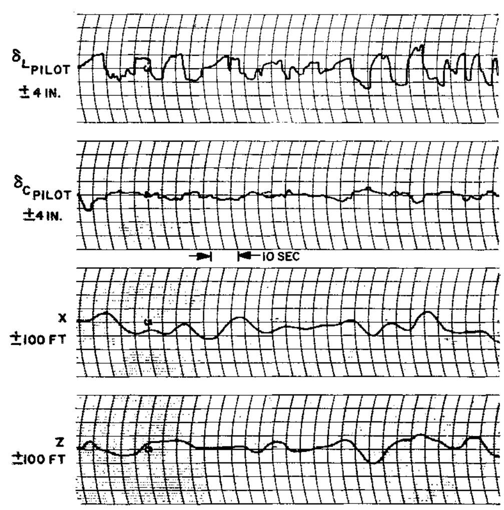

Fig. 1 Pilot activity and position errors (simulated CH-47A helicopter and stability augmentation system).

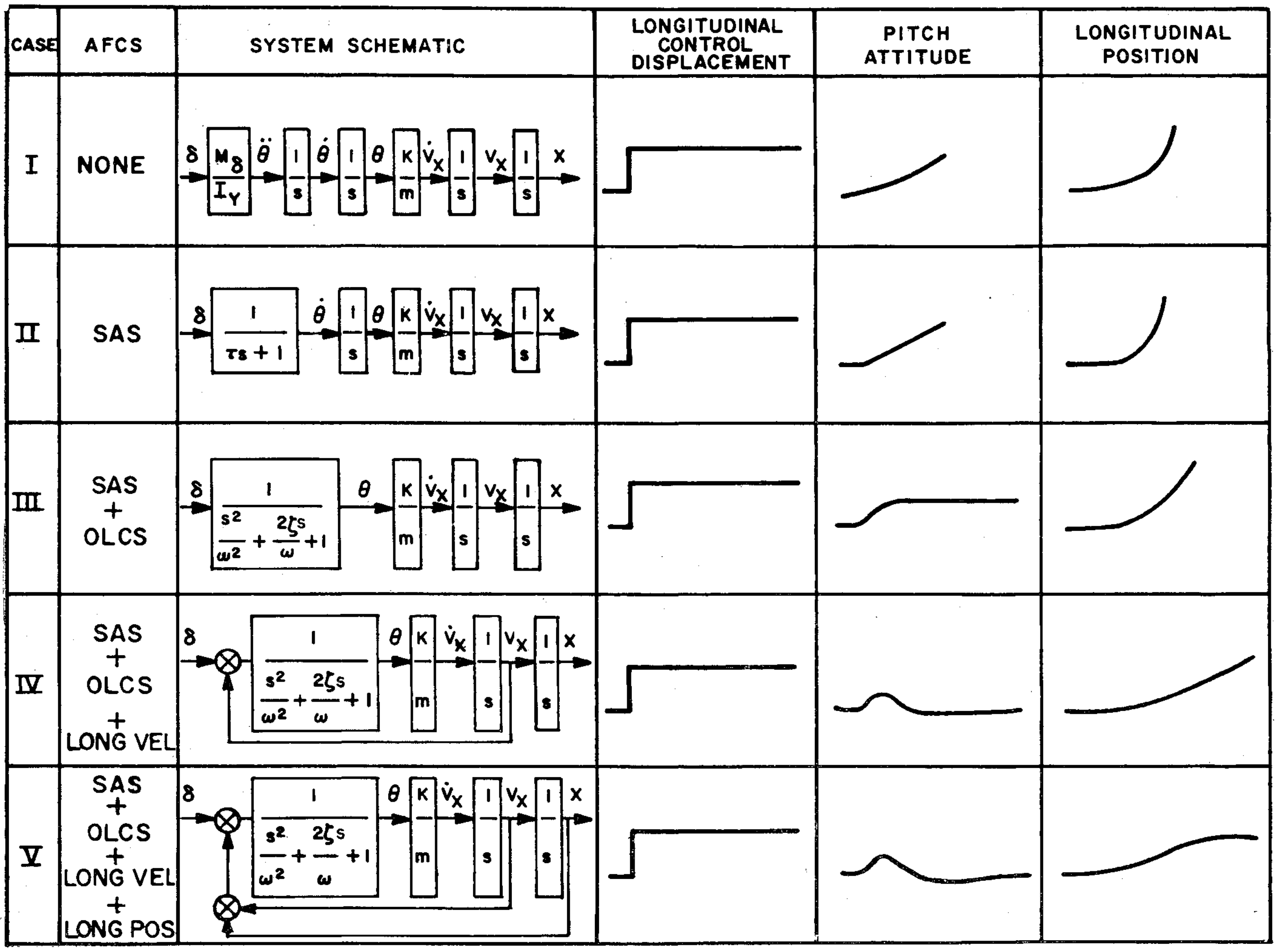

Fig. 2 Response characteristics of hover AFCS.

details are discussed later in the paper, indicate that the pilot's continuous and nearly total attention is required to perform this task.

The underlying mathematics of the problem are demonstrated by case I of Fig. 2, which shows that for the unaugmented helicopter, the transfer function of aircraft positional response to pilot inputs is fundamentally a fourth-order integration.[1] The problem of reducing pilot effort required to hover the helicopter is clearly related to the reduction of this transfer function to one of lower-order integration. This can, in principle, be achieved by successive feedback loop closures, as shown in Fig. 2. The HAS described by this paper is based on this principle. In the implementation of the HAS, a second problem was also considered, that of equipment complexity. To circumvent this problem, the following restrictions were placed on the equipment design: that only components of automatic pilot quality were to be used; and that the total complexity of the HAS (as measured by weight, volume, cost, etc.) was to be limited to a fractional part of that of an automatic pilot.

Design Approach

Preliminary analyses, as indicated in Fig. 2, show that feedback of signals proportional to aircraft acceleration, velocity, and position relative to the earth, is required to obtain the desired path stabilization. At least two approaches are available to obtain these signals: sensors mounted on a simplified inertial platform, or strapdown sensors and axis conversion. To retain maximum flexibility, the latter approach was chosen for at least the first phase of the development. It should be noted that the mounting of accelerometers directly on the gimbals of a vertical gyroscope still appears worthy of further investigation.

Thus, the feedback signals proportional to the helicopter's translation relative to earth and its derivatives were to be obtained from an orthogonal set of accelerometers mounted to the airframe. The output of these sensors is then processed in an analog computer that also has as an input the angular relationship of the aircraft axes to the desired inertial axes. This is obtained from a vertical gyroscope mounted with the same reference axes as the accelerometers. To simplify the equipment, a constant aircraft heading was assumed. This requires a heading hold function in the aircraft which may be achieved either automatically or by the pilot; neither is particularly difficult to realize in hover. The system thus described provides the fundamental sensor requirements for the HAS.

To allow the pilot to make minor corrections or to move from one point to another at near-zero velocities, it is necessary to add signals to the system which are proportional to pilot command inputs (collective and cyclic stick position). The design approach to the hover augmentation problem is thus defined and is summarized in Fig. 3.

System Design

The cues required for a pilot to hover an attitude-stabilized helicopter at a point in space have been hypothesized to be translational acceleration, velocity, position, and integral of position or aircraft trim. Under conditions of no wind or c. g. variations, the pilot can control the accelerations along

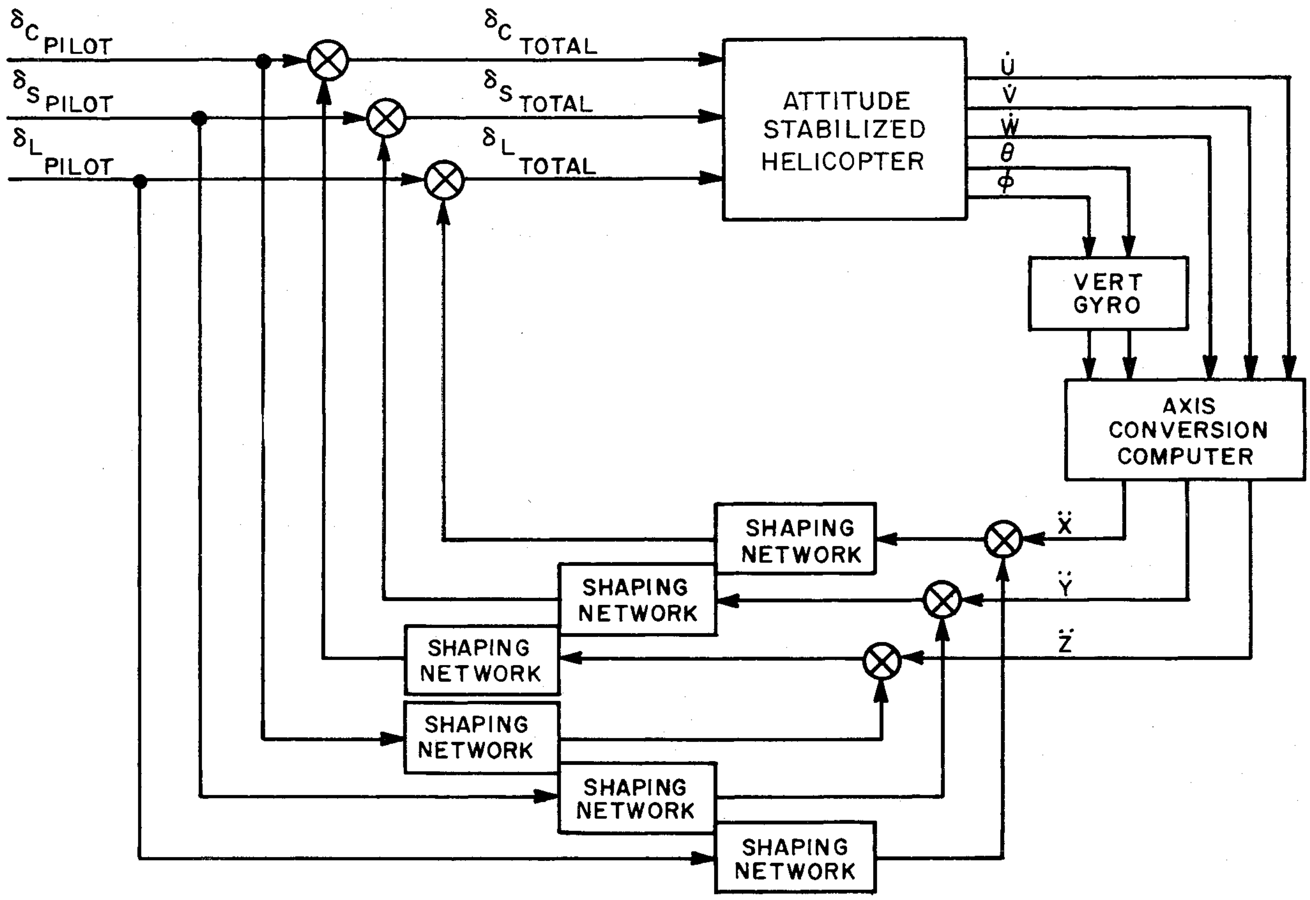

Fig. 3 Block diagram of hover augmentation system.

the longitudinal and lateral axes by controlling the aircraft pitch and roll attitudes. However, under gusty conditions, maintaining attitude will result in translation from the desired hover point due to the change in trim required to hold zero ground speed in the moving air mass. The purpose of the HAS is to reduce the pilot's task at hover by placing the control of the translational accelerations and velocities in an automatic flight control system (AFCS), rather than with the pilot.

A linear approximation of the helicopter pilot's transfer function at hover was assumed to be

$$\delta_{\text{pilot}} = K_{\dot\theta} + K_{\theta} + K_{\dot X} + K_{X} + K_{\int X} \qquad (1)$$

for the unstabilized aircraft. From Fig. 2 it can be seen that the pilot's transfer function can be reduced by successive loop closures in the AFCS with the simplest form being

$$\delta_{\text{pilot}} = K_{\int X} \qquad (2)$$

for case V.

The HAS is intended to provide a configuration like that of case IV of Fig. 2, so the pilot's transfer function is reduced to

$$\delta_{\text{pilot}} = K_{X} + K_{\int X} \qquad (3)$$

These assumptions have been shown to be valid in system verification studies in which simulated pilot transfer function showed good correlation with human pilots. In these initial studies, the CH-47A was chosen as the aircraft model.

To simplify the task of reducing the CH-47A equations of motion to transfer function form, only the longitudinal-vertical axes were used. This provides one rotational and two translational degrees of freedom.

The dynamics of the longitudinal-vertical aircraft equations were modified by the inclusion of the pitch attitude rate and displacement [SAS and outer loop control system (OLCS)] feedbacks. The feedback compensations needed to stabilize the pitch attitude had been determined in previous work done by Sperry Phoenix.[2] The aircraft and control system equations are presented in matrix form in Table 1. The solution of the matrix of Table 1 resulted in the transfer functions of Table 2. These transfer functions are the basis of the HAS compensation and dynamics study.

The criterion for acceptable dynamic response of the system was established as a frequency of not less than 0.5 rad/sec nor greater than 5 rad/sec, and a damping ratio greater than 0.45 of critical. These restrictions result in an overshoot of not more than 20% to a step input and control frequency requirements, which are within the normal frequency range of the pilot. Several ratios of velocity to acceleration gain were chosen and conventional root locus techniques were used to determine the limiting gains for each ratio.

Figure 4 is a root locus plot in the S plane showing the variation in root location as the ratio of velocity to acceleration feedback is varied with the maximum gain, which yields

Table 1 CH-47A hover equations of motion (including SAS and OLCS)

$-\ddot X - 0.178\dot X + 0.0059\dot Z + 1.18\dot\theta - 32.2\theta + 0.098\,\delta_{L\text{total}}$	=	$-0.0178\,u_{\text{gust}}$
$-0.185\ddot X - 0.675\dot X - \ddot Z - 0.434\dot Z + 0.197\dot\theta - 5.95\theta$	=	$-0.675\,u_{\text{gust}}$
$-0.017\dot X + 0.00234\dot X - \ddot\theta - 3.27\dot\theta + 0.312\,\delta_{L\text{total}}$	=	$-0.017\,u_{\text{gust}}$
$\ddot\delta_{L\text{total}} + 14.0\,\delta_{L\text{total}} - 14.0\,\delta_{L\text{SAS}} - 14.0\,\delta_{\text{OLCS}}$	=	$14.0\,\delta_{L\text{ pilot}}$
$7.96\ddot\theta + 32.0\ddot\theta + \ddot\delta_{L\text{SAS}} + 0.558\,\dot\delta_{L\text{SAS}} + 0.015\,\delta_{L\text{SAS}}$	=	0
$10.8\theta + \delta_{L\text{OLCS}}$	=	0

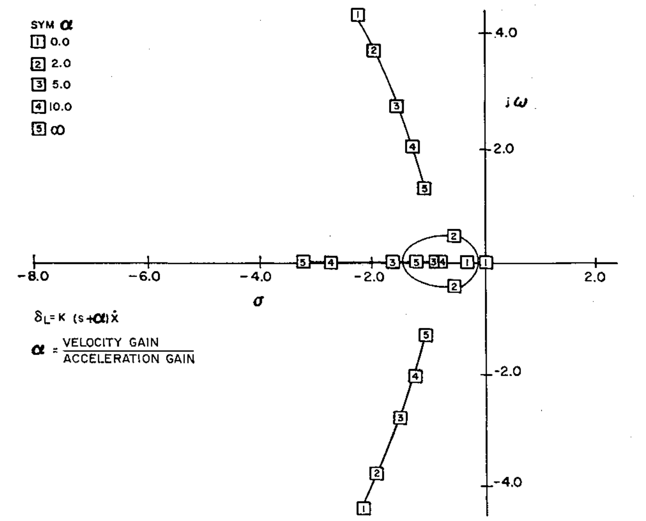

Fig. 4 Effect of varying ω (K required for ζ = 0.45 short period).

acceptable dynamics. Compensation 1 was eliminated because the dominant roots result in an instability. Compensation 5 was undesirable due to the high static gain required for this compensation. The remaining compensations are all acceptable from a dynamic standpoint. However, compensation 3 provides a good compromise between HAS static gain and aircraft steady-state velocity in response to a gust.

The vertical axis HAS compensation requirements are slightly different from the longitudinal axis. The characteristics of the vertical axis are such that a first-order response of velocity to a pilot input or a gust results. To decrease the static response to a gust input, the frequency must be increased. So that similarity between axes would be maintained, the compensation ratio of velocity to acceleration gains was again chosen to be 5. This compensation produces a vertical axis time constant of approximately 0.25 sec compared to 2.5 sec in the unaugmented aircraft.

Since the HAS is designed to aid the pilot in hovering and not provide an absolute position reference, the use of a long time constant lag in place of a perfect integrator to derive velocity was considered. This further reduces the static gain of the HAS. Also, to reject steady-state errors associated with the axis conversion from body axis to earth reference accelerations, a long time constant washout was considered desirable. Thus, the HAS compensations for the longitudinal and vertical axes were of the following form:

$$\delta_{L_{\mathrm{HAS}}} = [0.433s(s+5)]/(s+0.01)^2\ddot{X} \quad (4)$$

$$\delta_{C_{\mathrm{HAS}}} = [0.393s(s+5)]/(s+0.01)^2\ddot{Z} \quad (5)$$

Solving the equations of motion of Table 1, with the inclusion of the aforementioned HAS compensations, results in the transfer functions of Table 3.

The static gains of the resulting system are the same as those of the unaugmented airplane. However, in the frequency range of interest, a significant reduction in the effects of an external disturbance is achieved with the HAS.

System Mechanization

In addition to the dynamic requirements given previously, a HAS system error requirement was established at the beginning of the program. This requirement was that errors in the system should not produce a velocity error greater than 5 fps at the end of 30 sec. This results in an allowable system error of not more than 0.005 g in the computed inertial accelerations.

Consistent with this requirement, a gyro verticality error of $\pm 0.2°$ was established, and was met by specially "tuning" a standard autopilot unit. In addition to the vertical gyro tuning, the periodic variations in verticality were measured to determine their effect on the HAS. These variations were found to be small and random in nature, and thus of little consequence.

The axis conversion equations are:

$$\dot{V}_X = \dot{u}(\cos\theta\cos\psi) + \dot{v}(-\sin\psi\cos\phi + \cos\psi\sin\phi\sin\theta) + \dot{w}(\sin\psi\sin\phi + \cos\psi\cos\phi\sin\theta) \quad (6)$$

$$\dot{V}_Y = \dot{u}(\cos\theta\sin\psi) + \dot{v}(\cos\psi\cos\phi + \sin\psi\sin\phi\sin\theta) + \dot{w}(-\cos\psi\sin\phi + \sin\psi\cos\phi\sin\theta) \quad (7)$$

$$\dot{V}_Z = \dot{u}(-\sin\theta) + \dot{v}(\sin\phi\cos\theta) + \dot{w}(\cos\theta\cos\phi) \quad (8)$$

By requiring that the aircraft heading be stabilized either by the pilot or AFCS, and assuming the product of the sines of two angles is 0 and the cosine of a single angle is 1, the equations reduce to

$$\dot{V}_X = \dot{u} + \dot{w}\sin\theta \quad (9)$$

$$\dot{V}_X = \dot{v} - \dot{w}\sin\phi \quad (10)$$

$$\dot{V}_Z = \dot{w}\cos\theta\cos\phi - \dot{u}\sin\theta + \dot{v}\sin\phi \quad (11)$$

Table 2 CH-47A transfer functions (including SAS and OLCS)

Δ	$= s(s-0.11)(s+0.03)(s+0.21)(s+0.42)\times(s+11.6)(s+3.05\pm j2.87)$
$\dfrac{X}{u_{\mathrm{gust}}}$	$= \dfrac{0.178\,(s-2.7)(s+0.03)(s+0.58\pm j0.15)\times(s+10.6\pm j1.16)}{\Delta}\ \dfrac{\mathrm{ft}}{\mathrm{fps}}$
$\dfrac{Z}{u_{\mathrm{gust}}}$	$= \dfrac{0.672s(s+0.04)(s+0.10)(s+11.6)\times(s+3.04\pm j2.88)}{\Delta}\ \dfrac{\mathrm{ft}}{\mathrm{fps}}$
$\dfrac{X}{\delta_L}$	$= \dfrac{1.37(s-7.2)(s+0.03)(s+0.43)(s+0.53)\times(s+14.2)}{\Delta}\ \dfrac{\mathrm{ft}}{\mathrm{in.}}$
$\dfrac{\theta}{\delta_L}$	$= \dfrac{4.36s\,(s+0.02)(s+0.03)(s+0.43)(s+0.53)}{\Delta}\ \dfrac{\mathrm{rad}}{\mathrm{in.}}$
$\dfrac{Z}{\delta_C}$	$= \dfrac{-9.06(s-0.11)(s+0.03)(s+0.21)(s+11.6)\times(s+3.07\pm 2.85)}{\Delta}\ \dfrac{\mathrm{ft}}{\mathrm{in.}}$

Table 3 CH-47A transfer functions (including SAS, OLCS, and HAS)

Δ	$= s(s-0.002)(s+0.001)(s+0.8)(s+1.46)(s+4.0)\times(s+11.8)(s+0.0002\pm j0.001)(s+1.55\pm j2.8)$
$\dfrac{X}{u_{\mathrm{gust}}}$	$= \dfrac{-0.025(s-2.09)(s+0.01)^2(s+0.77)(s+4.05)\times(s+9.7)(s+10.6)(s+0.0003\pm j0.002)}{\Delta}\ \dfrac{\mathrm{ft}}{\mathrm{fps}}$
$\dfrac{Z}{u_{\mathrm{gust}}}$	$= \dfrac{-0.147s\,(s+0.00002)(s+0.01)^2(s+0.87)\times(s+1.56)(s+11.8)(s+1.49\pm j2.8)}{\Delta}\ \dfrac{\mathrm{ft}}{\mathrm{fps}}$
$\dfrac{X}{\delta_L}$	$= \dfrac{1.37(s-7.2)(s+0.01)^4(s+0.53)(s+4.0)\times(s+14.3)}{\Delta}\ \dfrac{\mathrm{ft}}{\mathrm{in.}}$
$\dfrac{\theta}{\delta_L}$	$= \dfrac{4.36s\,(s+0.01)^4(s+0.021)(s+0.53)(s+4.0)}{\Delta}\ \dfrac{\mathrm{rad}}{\mathrm{in.}}$
$\dfrac{Z}{\delta_c}$	$= \dfrac{-1.98(s-0.0019)(s+0.0014)(s+0.01)^2\times(s+0.88)(s+1.46)(s+11.8)(s+1.55\pm j2.8)}{\Delta}\ \dfrac{\mathrm{ft}}{\mathrm{in.}}$

With the previous assumptions, the resulting equations have an error of less than 5% for the attitudes and accelerations normally encountered at hover ($\pm 10°$ attitude and ± 0.1 g accelerations).

Implementation of the HAS axis-conversion computer was accomplished using state-of-the-art electronic techniques. The total allowable error, which had been established as less than 5%, was achieved from this computer. Standard autopilot quality accelerometers were specified for the system with a range of ± 0.5 g in the longitudinal and lateral axes and 1 ± 0.5 g in the vertical axis. Use of these components (gyro, computer, and accelerometers, as shown in Fig. 5) results in a maximum system error of less than the allowable 0.005 g.

Although the system is designed for use with existing aircraft actuators, the actuator characteristics must obviously meet certain minimum requirements. The following requirements were determined during the verification studies: break frequency—greater than 3 cps; threshold—less than 0.5% of full stick travel; velocity—greater than 25% full stick travel per second.

Verification Studies

These studies were divided into two phases. Phase I was intended to verify the compensations chosen during the analytical investigations, design the command augmentation in each axis, and allow investigation of parameter variation on system performance. In phase II, human operators were included in the system through a helicopter cockpit simulator interface.

During phase I, a simulated pilot was utilized to provide repeatability during the investigation of system variables. The original assumption of a pilot transfer function,

$$\delta_{\text{pilot}} = K_{\dot\theta} + K_{\theta} + K_{\dot X} + K_X + K_{\int X} \qquad (12)$$

was found to require only the $K_{\dot X}$, K_X, and $K_{\int X}$ gains plus a first-order lag at 1 cps to control a pitch rate stabilized helicopter. Inclusion of the K_θ gain improved system performance, but was not necessary for stability. With the attitude hold loop included in pitch, the pilot transfer function gain was only slightly changed from the stability-augmented aircraft configuration. Inclusion of the HAS in the system reduced the required pilot transfer function to

$$\delta_{\text{pilot}} = K_X + K_{\int X} \qquad (13)$$

as was theorized during the initial portions of the analytical

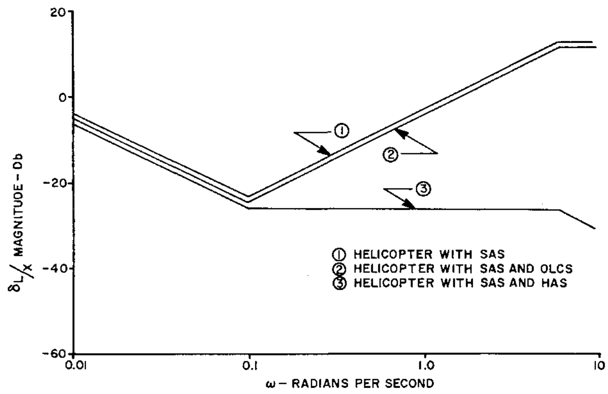

Fig. 6 Longitudinal simulated pilot (hover at a point).

studies. A summary of the required pilot transfer functions is presented in Fig. 6. From Fig. 6 it is obvious that less high frequency activity is required of the pilot when the HAS is included in the system.

Design of the longitudinal-vertical axis command augmentation system (CAS) was done on a transient response basis during the verification studies. The design criterion was that the short period rate of change of acceleration (analogous to pitch rate) to a control step should be the same for the HAS-CAS combination as it is for the helicopter with SAS only. However, in the long period, a constant longitudinal velocity is desired rather than constant jerk ($\dddot{X}$) which results from the SAS only. In the vertical axis, the response of the unaugmented aircraft to a control step input is satisfactory, and the HAS-CAS was designed to cause no change in this mode. Figure 7 shows the aircraft longitudinal and vertical response to step control inputs for the HAS-CAS configuration and the SAS only configuration.

Investigation of the HAS with gain and time constant variations and actuator, and accelerometer and gyro nonlinearities, showed that parameter variations of 25% could be tolerated without severe degradation of performance and with no unstable system operation. The nonlinearities such as deadzone or breakout, and velocity limits, did not seriously affect system performance if maintained at the values specified previously.

The phase II verification studies put the human operator in the control loop. The helicopter cockpit simulator was used to provide the interface between pilot command and

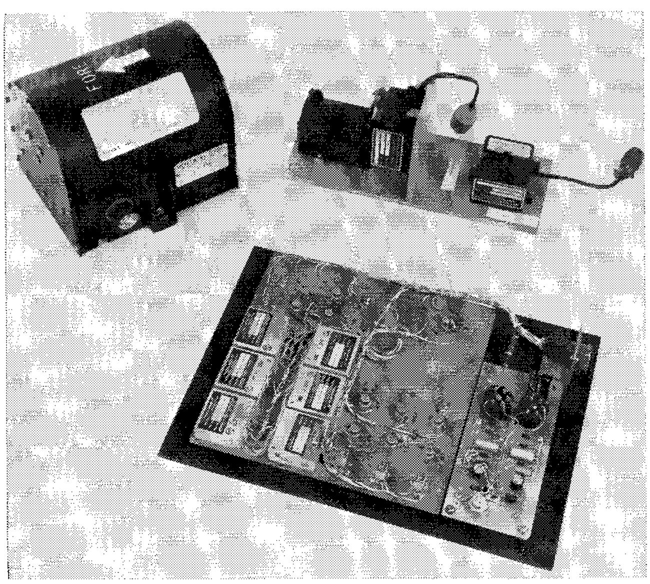

Fig. 5 Hover augmentation system hardware.

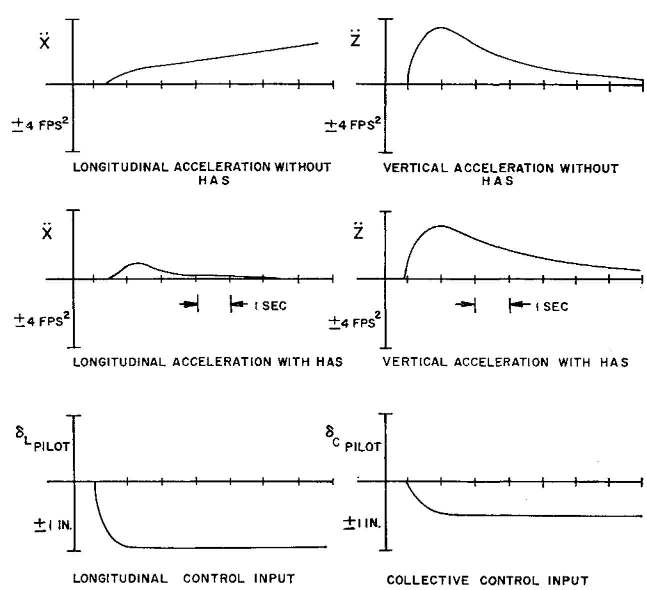

Fig. 7 System response with and without HAS.

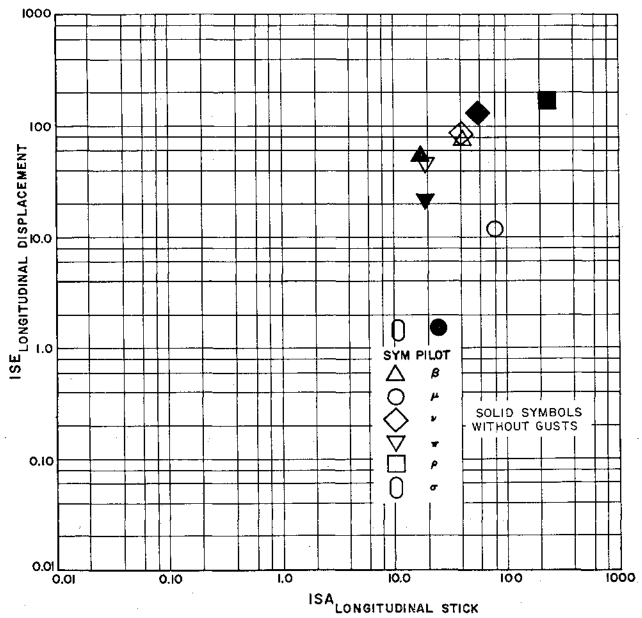

Fig. 8 Variation in pilot activity and position error—longitudinal (SAS only).

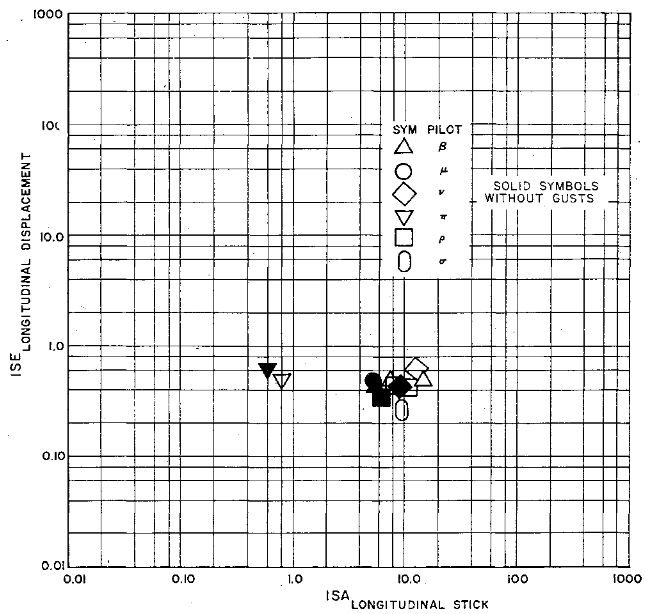

Fig. 10 Variation in pilot activity and position error—longitudinal (SAS and HAS).

the analog computer. Interface between the analog computer and the pilot was via cockpit instruments for attitude information and an X-Y plotter for displacement information. The X-Y plotter was scaled to produce a 1-in. motion/10 ft of aircraft motion.

During these studies, repeatable "random" gusts were used to perturbate the aircraft so that evaluation of pilot activity and position error could be evaluated. The maximum gusts encountered were approximately ± 10 fps.

Of the five operators for whom quantitative data were taken, three were pilots (two with helicopter ratings) and two were engineers with no pilot training. After a familiarization period of 30 min to 1 hr, each operator was asked to perform certain tasks. Integral square error (ISE) of longitudinal and vertical aircraft positions and the integral square of activity (ISA) of longitudinal and collective control were recorded to provide a quantitative comparison of the various automatic flight control system configurations.

Figures 8 and 9 show the variation between pilots in the performance indices for the longitudinal-vertical axes with only the SAS loop closed. The variation between pilots in both activity and error is quite marked. Pilot σ is the simulated pilot described earlier in this paper. Although one pilot was able to approximate the position error of the completely analog, simulated pilot, his control motion index is higher. A tendency to overcontrol was noted among the pilots who generally agreed that the configuration was difficult to control. The addition of gust noise to the simulation affected all of the pilots, but not in a consistent manner.

Figure 9 shows a similar dispersion to Fig. 8, but the error criteria are a magnitude smaller. Since the aircraft response to a control step in the vertical axis yields velocity rather than jerk as in the longitudinal axis, the pilot does not have to anticipate the motion of the aircraft. For this reason, there was less tendency to overcontrol among the pilots.

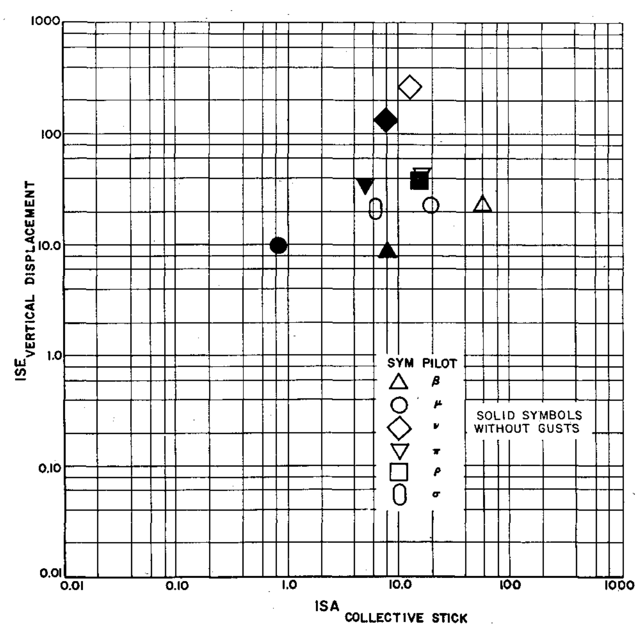

Fig. 9 Variation in pilot activity and position error—vertical (SAS only).

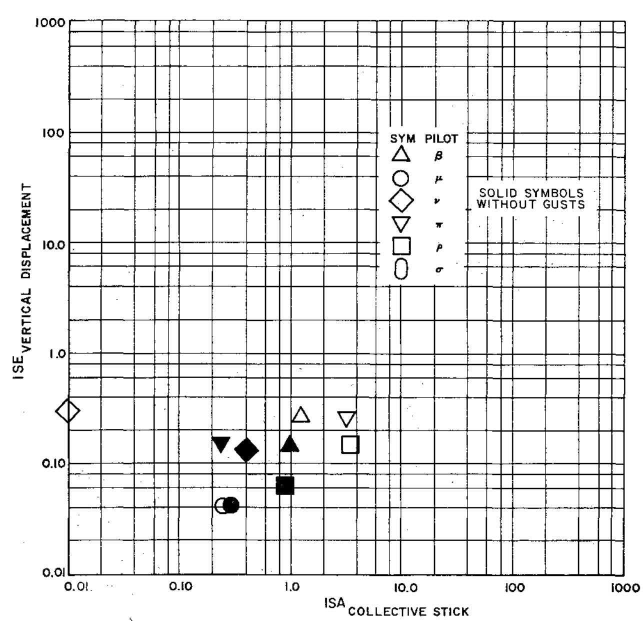

Fig. 11 Variation in pilot activity and position error—vertical (SAS and HAS).

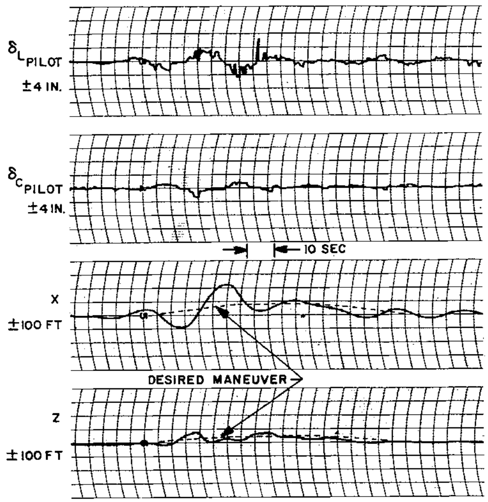

Fig. 12 Maneuver with SAS.

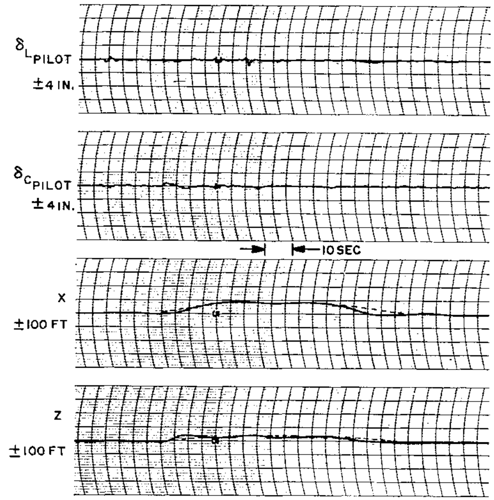

Fig. 13 Maneuver with SAS and HAS.

Figures 10 and 11 are for the aircraft with SAS and HAS. A significant reduction in dispersion between pilots and an improvement in accuracy with simultaneous reduction in effort are apparent from these figures. With the inclusion of the HAS, the effect of gusts on pilot performance is also reduced in both axes.

With this feedback configuration, the response to a stick step in both the longitudinal and vertical axes produces a velocity. The vertical axis time constant is approximately 0.25 sec, whereas the longitudinal axis has about a 2-sec lag. The differences in time constant are probably the cause of the difference in performance levels between axes. The time constant of the longitudinal axis can be reduced by adding a rate of command signal to the CAS. However, it is obvious that quickening the response by this method will result in large pitch attitude accelerations and attitudes. Evaluation of quickened longitudinal response and final calibration of the CAS will be done as part of the flight test program.

The maneuvering response of the helicopter near hover was studied during this program, with the human pilot controlling the aircraft position. Time histories of one pilot who was representative of the group are presented in Figs. 12 and 13. These figures show an improvement in the maneuverability between points as the aircraft dynamics are varied from a pitch rate response to a linear velocity response in the longitudinal axis. Not only is the aircraft motion more closely controlled but, also, the pilot activity and attention requirements are reduced, allowing the pilot more freedom to perform other tasks.

Conclusions

A HAS made up of a small number of simple components has been built which greatly reduces the pilot effort and attention required to hover a helicopter. Use of the HAS allows the helicopter to be hovered at a point in space with a reduction of error and of pilot activity by an order of magnitude when compared to the SAS-equipped helicopter alone. The pilot's task is reduced from one requiring full-time attention with constant corrective inputs with the SAS alone, to one requiring only sporadic attention with corrective inputs required every 15 sec or so when the HAS is used. In addition, the use of the HAS normalizes the pilot's hovering performance such that a relatively poor pilot does a good a job as an expert.

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[2] McBrayer, J. S. and Robinson, R. W., "A fail-functional stability augmentation system," J. Am. Helicopter Soc. **10,** 25 (November 1965).