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Computer Simulation of a Single Pilot Flying a Modern High-Performance Helicopter

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COMPUTER SIMULATION OF A SINGLE PILOT
FLYING A MODERN HIGH-PERFORMANCE HELICOPTER

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SUMMARY

This report presents a computer simulation of a human response pilot model able to execute operational flight maneuvers and vehicle stabilization of a modern high-performance helicopter. Low-order, single-variable, human response mechanisms, integrated to form a multivariable pilot structure, provide a comprehensive operational control over the vehicle. Evaluations of the integrated pilot were performed by direct insertion into a nonlinear, total-force simulation environment provided by NASA Lewis. Comparisons between the integrated pilot structure and single-variable pilot mechanisms are presented. Static and dynamically alterable configurations of the pilot structure are introduced to simulate pilot activities during vehicle maneuvers. These configurations, in conjunction with higher level, decision-making processes, are considered for use where guidance and navigational procedures, operational mode transfers, and resource sharing are required.

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INTRODUCTION

The fundamental task of pilot-based flight control is maintaining a stabilized control over aircraft attitudes, rates, and orientations. When required to execute a flight control maneuver, the pilot must guide the vehicle through a specific set of orientations while maintaining a stabilized control over the entire vehicle. The complex couplings and interactions that are inherent to helicopter behavior must be adequately dealt with to ensure a satisfactory flight control. The low-order, single-variable, human response pilot mechanisms presented in reference 1 provide adequate control of single flight control variables. The pilot mechanisms model the considerations and tactics that a human pilot incorporates when operating a specific cockpit control mechanism by visual assessment of instrumentation or external cues (fig. 1). This pilot model is based on an understanding of the helicopter's dominant response characteristics. The single-variable pilot mechanism encounters difficulty

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however, in its intrinsic inability to monitor and control the reactions of the remaining flight control variables.

A human pilot uses all cockpit control mechanisms for operational control while employing visual, audio, and other feedback cues. For the purpose of simulation, a comprehensive human response pilot model is formed by integrating various single-variable human response mechanisms into the multivariable structure shown in figure 2.

A set of human response mechanisms is used in decoupled single-variable compensation arrangements to implement the substructure of the multiloop configuration. This pilot structure offers complete access to the cockpit control mechanisms (lateral and longitudinal cyclic stick, main rotor collective stick, tail rotor collective pedals), but allows visual feedback of only four flight control variables. The structural configuration of the pilot is defined by the manner in which the visual feedback is interpreted and applied to the control mechanisms via a specific set of human response mechanisms. The limitations of each configuration make each applicable to only a specific set of flight control maneuvers. Thus, each type of maneuver is associated with a specific structural configuration.

During piloted missions, flight control operations are subject to changes as the mission progresses, and, thus, the pilot structure requires modification (i.e., change of structural configurations). The change in structure can be perceived as an alteration of pilot feedback caused by shifting visual assessment from one cockpit instrument to another. Decision-making processes can be introduced that select and activate the configurations best suited for a specific maneuver. Modifying the pilot's structural configuration is necessary because of the restrictions associated with the helicopter's limited number of cockpit control mechanisms and feedback paths available to the pilot. An additional complication arises in the limitations associated with the human visual system's information processing capabilities. The pilot is, therefore, forced to compensate by expanding his capabilities via structural modification.

This report presents the applications of various sets of human response pilot mechanisms, developed in reference 1, operating within multivariable flight control structures. The structural configuration associated with a flight control maneuver is selected from an evaluation of pilot attributes that are best suited for accomplishing the maneuver objectives. Additional low-order helicopter models and pilot mechanisms will be introduced to provide control of vehicle attitudes and rates associated with specific flight maneuvers. Higher level control processes will be introduced to achieve a wider variety of flight maneuvers and to overcome the limitations associated with the control structure. Comparisons of the single-variable pilot mechanisms (ref. 1) with those introduced in this paper will be made to show the superior response characteristics of the multivariable pilot structures.

SYMBOLS

ALT	altitude, ft
\dot{ALT}	time rate of change of altitude
a	pole time constant

a_{BETA}	time constant of pole in sideslip models, s^{-1}
BETA(S)	Laplacian of vehicle sideslip, deg
b	pole time constant
C	convex function
e	error signal
G	transfer function
$G_{\text{BETA}}(S)$	transfer function of tail rotor collective pedals to sideslip angle, deg/in.
$G_{\text{PLT}}^{\text{BETA}}(S)$	transfer function of human response sideslip control pilot, in./deg
K_{BETA}	gain of sideslip model, $(\text{in.}\cdot\text{s})^{-1}$
K_{β}	gain of sideslip control pilot, $\text{in.}/\text{s}^2$
PED(S)	Laplacian of tail rotor collective pedal deflection, in.
PHI	roll angle, ϕ
PLT	pilot
PSI	yaw angle, ψ
S	Laplacian variable
THETA	pitch angle, θ
V	vehicle velocity, kn
α	value of convex function
β_a	unit equalization scalar for convex functions
β_r	unit equalization scalar for convex functions
ϵ	ramp constant for convex functions

FLIGHT CONTROL CONFIGURATIONS

A fundamental task associated with pilot-based flight is the operational control of helicopter attitudes and rates for use in flight maneuvers. Higher level tasks, such as narrow bandwidth guidance or navigation processes, are superimposed on the fundamental tasks to broaden the range of pilot control. The pilot model (fig. 2) provides the fundamental control of helicopter

attitudes and rates via a decoupled multivariable structure. The command structure associated with this pilot model assumes the presence of high-level processes to provide the command sequencing. The high-level processes issue commands in the form of maneuvers associated with specific vehicle attitudes or rates. A commanded maneuver is a set of vehicle attitudes and/or rates that define the new orientations that the helicopter must attain. The pilot's task is to manipulate the control mechanisms in such a way as to reorient the helicopter. The intricacy of a commanded maneuver is defined by the number of attitudes and/or rates that are simultaneously involved in the operation.

During the initial phases of a flight control maneuver the pilot structure is configured to provide the visual feedback that is required (i.e., pilot monitors the appropriate instruments). The response characteristic of a given configuration is defined by the manner in which the visual feedback is used during the execution of the maneuver. A static configuration is a structural configuration whose feedback paths are not altered during the execution of the maneuver (e.g., speed control in a car by visual feedback of the speedometer). A dynamic configuration is a structural configuration whose feedback paths are modified in some way during the execution of the maneuver. The type of configuration used is strictly dependent on the maneuver that is to be performed.

The flight control objectives associated with simple maneuvers require the control of only primary vehicle attitude or rate. The remaining secondary variables are monitored and regulated to preserve the stabilized aspects of the vehicle orientation. This type of operation can be performed by the static configuration shown in figure 3. During the execution of the maneuver, this structural configuration provides direct control and regulation of the attitudes and rates that are critical to the operation.

Implementing this type of static configuration involves the selection of a primary attitude or rate and a set of secondary attitudes or rates that are considered critical to the maneuver. Only the primary flight control variable is controlled to achieve the specific maneuvering characteristics. The regulated secondary variables provide stability while in the desired orientation. It is important to realize that only one primary and three secondary variables can be dealt with by a configuration of this type. A set of static configurations can, therefore, be created to provide a wide range of maneuvering capabilities.

FLIGHT MANEUVERS FOR STATIC CONFIGURATIONS

The maneuvers considered for use with the static pilot configuration are as follows:

- Pitch angle
- Altitude position
- Yaw/heading
- Vertical rate
- Turn coordination

It is important to note that the first three maneuvers use the same configuration. The only difference will exist in the flight control variable that is commanded.

Pitch Angle Maneuver

The pitch angle maneuver is commanded to achieve pitch angle control. The redirection of the main rotor thrust vector directly induces both velocity and altitude variations. The velocity variations require a higher level process because of the limitations of the feedback structure. It is important to note that the higher level process must use some type of shared operation if the velocity is to be controlled. The specifications for this maneuver are as follows:

- Primary variable:
Pitch angle, θ
- Secondary variables:
Roll angle, ϕ
Yaw angle, ψ
Altitude, ALT

The yaw, roll, and altitude pilots must suppress the disturbances caused by the redirection of the main rotor thrust vector.

Altitude Position Maneuver

In the helicopter altitude maneuver, an altitude-positioning control must be achieved to provide direct altitude modification over limited displacements. Level flight and correct heading are maintained. Specifications are as follows:

- Primary variable:
Altitude, ALT
- Secondary variables:
Pitch angle, θ
Roll angle, ϕ
Yaw angle, ψ

Once again, the yaw/heading control provides the counter torque for the main rotor. The pitch control pilot compensates for main rotor thrust-related pitch variations.

Yaw/Heading Maneuvers

The yaw/heading angle is position controlled to allow tracking of step- and ramp-type commands. Heading corrections and regulation are achieved by step-commanded operations. Flat turns (i.e., nonbanked, uncoordinated level turn with no altitude variation) are obtained from ramped commands. Level vehicle orientations will be maintained for both forms of command. The specifications are as follows:

- Primary variable:
Yaw angle, ψ

- Secondary variables:
Pitch angle, θ
Roll angle, ϕ
Altitude, ALT

Yaw rate maneuvers execute flat turns and are, therefore, suggested for low-speed flight conditions (20, 40, and 60 kn) because of sluggish high-speed aerodynamic effects. The roll position pilot suppresses the coupled disturbance effects induced by the tail rotor countertorque.

Vertical Rate Maneuver

The vertical rate maneuver is commanded to achieve an ascent rate control. A level vehicle flight orientation is preserved while the correct heading is maintained. The following specifications are, therefore, appropriate:

- Primary variable:
Vertical rate, ALT
- Secondary variables:
Pitch angle, θ
Roll angle, ϕ
Yaw angle, ψ

The yaw/heading control provides an important compensating regulation by suppressing the main rotor torque reaction disturbances. The pitch position pilot provides a rejection of the coupled reactions of the pitch angle associated with the increase in the main rotor torque.

Coordinated Turn Maneuver

The purpose of a coordinated turn maneuver is to allow heading modification without altitude loss or sideslip. Turn coordination is achieved by suppressing the lateral body acceleration while maintaining a commanded roll attitude. This maneuver only considers the execution and maintenance of the coordinated turn. Higher level processes are expected to monitor the heading and to switch out of this maneuver when the desired heading is reached. The specifications are as follows:

- Primary variable:
Roll angle, ϕ
- Secondary variables:
Pitch angle, θ
Sideslip angle, β
Altitude, ALT

To achieve the lateral acceleration suppression, it is necessary to introduce a sideslip reduction pilot. This pilot monitors the effect of the lateral acceleration by assessing the slip ball. Control is constructed by using the tail rotor pedals. Models of sideslip responses and their associated pilots are shown in the following.

The primary response characteristics of the sideslip of the nonlinear simulation environment (ref. 2) are given by

$$G_{\text{BETA}}(S) = \frac{\text{BETA}(S)}{\text{PED}(S)} \approx \frac{K_{\text{BETA}}}{S + a_{\text{BETA}}} \quad (1)$$

The parameter values are shown in the following table:

V, kn	K_{BETA}^V , (s ²)-1	a_{BETA}^V , s ⁻¹
20	-3.25	0.08
40	-1.30	.20
60	-.87	.30
80	-.87	.30
100	-.87	.30

This table shows that the sideslip is far more pronounced at lower speeds. This is due, in part, to the aerodynamic effects that promote weather vaning of the fuselage at higher speeds.

The pilot mechanism (ref. 3) associated with the sideslip suppression is given by

$$G_{\text{PLT}}^{\text{BETA}}(S) = \frac{K_{\beta}(S + 0.8)e^{-0.25}}{S(S + 10)} \quad (2)$$

The parameters are listed in the following table:

V, kn	K_{β} , in/s ²
20	-0.25
40	-.45
60	-.55
80	-.55
100	-.55

The primary objective of this control configuration is to provide a yaw rate by commanding a roll angle displacement (ref. 4).

The use of the tail rotor pedals for sideslip reduction removes the heading regulation. The overall use of the coordinated turn requires some type of heading control operation. Heading control requires the operation of a higher level decision-making process that monitors the heading and dynamically reconfigures the system when the proper heading has been reached. The altitude position pilot provides the additional lift that is lost by the roll maneuver.

RESULTS OF STATIC CONFIGURATION INSERTION

The testing and evaluation of the static configurations were performed by inserting the individual configurations into the nonlinear helicopter simulation environment. The pilot performed specific flight maneuvers to determine the overall capability of the individual configuration. In general, the static configurations show a significant improvement over the single-variable pilots presented in reference 1. No substantial secondary disturbances were observed. To limit the pilot evaluation, only step commands are presented. In addition, only a comparison of the pitch control pilots is presented.

Pitch Angle Configuration

The responses of the static pitch angle configuration to a 5° step command can be seen in figures 4 to 11. The helicopter was initially in an 80-kn-trimmed flight condition. For comparison, figures 4, 5, 9, 10, and 11 (parts (b)) show the responses of the single-variable pilot mechanism developed in reference 1. It is important to note that the scales associated with the plots of the respective pilots may be substantially different. Figures 4(a) and 4(b) show the pitch angle responses. The large peaked overshoot is common to both, but the static pilot (fig. 4(a)) provides an enhanced settling. Figure 5 shows the pilot's operation of the longitudinal control mechanism. The initial response is similar, but the single-variable pilot (fig. 5(b)) shows a more substantial trim-tracking effort. This suggests that the static pilot (fig. 5(a)) is not confronted with the extreme disturbances that confront the single-variable pilot. Figures 6, 7, and 8 show the secondary regulation-control-mechanism deflections. The single-variable pilot's operation of these control mechanisms has been neglected because of the nonconnection which results in the deflections being zero. The static pilot's operations (figs. 6, 7, and 8) show distinct disturbance-tracking characteristics. The deflection patterns, however, show the signs of possible control mechanism saturation if the maneuver is maintained over a long interval.

Figure 9 shows the roll angle responses. The static pilot (fig. 9(a)) shows the significant improvement resulting from the augmentation of the regulation set. Figure 10 shows the yaw angle responses. Again, the static configuration (fig. 10(a)) shows the considerable enhancement associated with the regulation set, when compared with that of the single-variable pilot (fig. 10(b)).

Figure 11 shows the altitude responses. The static pilot response (fig. 11(a)) has once again achieved a vast improvement over the responses of the single-variable pilot (fig. 11(b)).

This comparison shows the significant improvement that is achieved by the employment of the multivariable pilot configuration. Similar improvements were noted with the other static pilot configurations when compared with the single-variable implementation. The remaining evaluations concern only the responses of the static configurations.

Altitude Position Configuration

The responses of the static altitude control configuration to a 10-ft step command are shown in figures 12 to 19. Initially, the helicopter was in an 80-kn-trimmed flight condition. Figure 12 shows the execution of a crisp step in altitude. Note the minimal overshoot. The pilot's operation of the collective is shown in figure 13. Figure 14 reveals a moderate, but quickly damped, transient in the pitch angle that has been accomplished by the pilot's compensating deflection of the longitudinal stick (fig. 15). This transient behavior is the result of the longitudinal couplings and the abruptness of the altitude maneuver.

Figure 16 displays the results of the roll angle regulation. This compensative action is the result of the main rotor torque-reactive disturbances that are induced in the lateral and directional planes. The actions taken by the pilot are shown in figure 17. The main compensative mechanism used to oppose the torque disturbances is the heading regulation. Figure 18 shows the yaw angle response to the influence of the main rotor torque reactions. The pilot's control operation to reject the disruptive effects can be seen in figure 19. The heading regulation plays a very important role when the flight maneuvers modify the main rotor thrust vector.

Yaw Angle Configuration

The responses of the static yaw angle configuration to a 10° step command can be seen in figures 20 to 27. Initially, the helicopter was in an 80-kn-trimmed flight condition. This command initiates a heading change which is executed as a flat turn. The abrupt change in heading induces a large sideslip. Flat turns produce an undesirable sideslip at all forward velocities because of their inherently uncoordinated operation. Figure 20 shows the yaw angle response to the step command. Note the steady-state error due to trim tracking in the later phases of the response. Trim tracking is also apparent in the pilot's operation of the tail rotor pedals (fig. 21). This tracking is due to the velocity reduction and the system type. Figure 22 shows the roll angle response. The transients in the roll angle are not as pronounced as expected. Figure 23 shows the pilot's operation of the lateral stick. Note the steady-state step in the deflection which is also due to trim tracking.

Figures 24 and 25 show the pitch angle response and the pilot's deflection of the longitudinal stick, respectively. Figure 25 shows the evidence of trim tracking in the steady-state step. Figure 26 and 27 show the altitude response and the associated operation of the main rotor collective stick. The lower type of the altitude control mechanism is a prime candidate for trim-tracking-related disturbances. This is evident in both figures.

The trim track disturbances, although clearly visible in the secondary regulation responses, are not significant enough to warrant any external intervention.

Vertical Rate Configuration

The responses of the static vertical rate configuration to a 15-ft/s step command are shown in figures 28 to 31. The helicopter was initially in a

60-kn-trimmed flight condition. These figures show only the responses of the primary and secondary variables. Figure 28 shows an excellent response to the command. The pitch angle response is shown in figure 29. The main rotor thrust couplings have once again disturbed the pitch angle with a moderate initial transient, but the secondary regulation has provided a quick suppression. The roll angle (fig. 30) shows only a small-scale disturbance. The yaw angle response (fig. 31) indicates the presence of main rotor torque disturbances. The response also shows that a reasonable rejection has been achieved.

Coordinated Turn Configuration

The responses of the static coordinated turn configuration to a 20° bank turn command are shown in figures 32 to 36. The helicopter was initially in 80-kn-trimmed flight. Only the responses of the primary and secondary variables are considered. Figure 32 shows a smooth roll angle response to the step command. The response of the heading angle (fig. 33) indicates that the turn is being executed. Note the transient response due to the settling of the roll angle and the coordination operations. Figure 34 shows the sideslip suppression and indicates that turn coordination has been achieved. The inherent loss of lift, due to the redirection of the main rotor thrust vector caused by the roll operation, results in the initial transient in the altitude (fig. 35). The altitude regulation provides an adequate recovery from the transient. Figure 36 shows the pitch angle response. The pitch angle control shows a satisfactory management of the disturbance.

Figure 37 shows roll angle response during the execution of the same 20° bank turn, but at 20 kn. Note that the roll response in this flight condition is slightly less refined.

DYNAMIC CONFIGURATIONS AND PROCESSES

To simulate the execution of more elaborate and wider ranging flight maneuvers, it is necessary to introduce operations that are external to the configurations discussed to this point. The actual extension to larger scale maneuvers is achieved by dynamically altering the internal system configuration. The internal system is considered the existing static, decoupled, multi-variable system. The alterations are mode shifting which allows the pilot to offer a multifunctional profile to the operational requirements.

An example of the need for this type of dynamic structure is seen in applications that require large-scale altitude modifications. Strict use of altitude position control can lead to control mechanism saturation or other adverse effects. A strategy for avoiding these problems is to implement a rate control operation when the positioning error is great and then to steadily transfer to a positioning configuration as the error lessens. This constitutes a dynamic translation that is a function of the error in position. From a human pilot standpoint, this can be seen as follows.

The pilot uses the altimeter as a rough estimator to determine the extent of the positioning. If the error is large enough, the pilot resorts to an altitude rate control via the vertical rate indicator. As the rate operation

continues, the pilot periodically checks the altimeter to determine the extent of the positioning error. As the error is reduced the pilot begins to monitor the altimeter more. The ratio of altimeter to vertical rate indicator is reduced as the positioning error is reduced. Finally, the pilot relies entirely on the altimeter as the positioning error approaches zero. A pictorial description of this process is shown in figure 38. When dealing with this type of a translational control, it is important to consider the manner in which the human interfaces with the control mechanism. The mechanism used by and associated with the human must be the same (i.e., the same hand is used to achieve an altitude position and a vertical rate via the collective stick). The control configuration used to achieve this type of operation is shown in figure 39.

This type of structure is a translational resource-sharing configuration. The resources in question are the main rotor collective stick and the pilot's operational control mechanism (arm/hand). The translation process uses the ascent rate and the positioning error to determine the transition factors that govern the manner in which the control authority is transferred. The resource-sharing structure can be directly added to the static altitude position configuration. The shared configuration is shown in figure 40.

The translational process considered here is a convex function given by

$$C = (1 - \alpha)\beta_a C_{ALT} + \alpha\beta_r C_{rate} \quad (3)$$

where

$$\alpha = \begin{cases} 1 & e_{ALT} > \epsilon_1 \\ \alpha_0 & \epsilon_2 \leq e_{ALT} \leq \epsilon_1 \\ 0 & e_{ALT} < \epsilon_2 \end{cases} \quad \beta_a, \beta_r \rightarrow \text{unit equalization scalars}$$

$$\epsilon_1 > \epsilon_2$$

The parameters associated with the convex operation are related to the manner in which the control is transferred. The actual dynamics of the translation depend on how the position error is interpreted.

For the purpose of this discussion, only a linear translation is considered. The linear translation uses the parameter dynamics shown in Figure 41. Figure 42 shows a 100-ft-altitude-position maneuver using the linear translational dynamics. The translational parameters are given by the following:

$$\begin{aligned} \epsilon_1 &= 50 \\ \epsilon_2 &= 25 \end{aligned}$$

This type of translation tends to provide the smoothest crossover, but it also has the longest interval of direct competition between the control processes. Direct mode shifting is desirable during the transition from level flight to a coordinated turn and during the return to level flight. Mode shifting is required in the tail rotor control operations. During level

flight, the tail rotor pedals are used primarily for handling adjustments and flat turns. When executing coordinated turns, the pedals provide the sideslip compensation. A graceful mode switch is needed during the entry of the turn and again in the later stages of the return to level flight. Figure 43 shows the regions where operational crossovers would be desirable during coordinated turn execution. Once again, the physical human mechanism (i.e., feet/legs) will be shared between the two control operations.

As long as heading and sideslip errors are relatively small, no special crossover process is needed. Thus, the mode switch can be generated by a guidance-type process that would implement large heading changes by the execution of coordinated turns. The translational parameters can be implemented by

$$\begin{aligned}\epsilon_1 &= 15 \\ \epsilon_2 &= 15\end{aligned}$$

This will create a direct mode switch at 15° of heading command deviation. It is important to note that the mode switching does not implement the heading control.

CONCLUDING REMARKS

The multivariable pilot configurations presented show a significant improvement in overall flight control execution when compared with the single-variable configurations of reference 1. In addition, the wide range of configurations that can be implemented allow the execution of far more complex flight maneuvers. The introduction of dynamic configuration modifications substantially increases the effectiveness of the static substructure by permitting the configuration to use the full range of available pilot mechanisms. To further enhance the manner in which the pilot responses are determined for the various flight conditions, some type of adaptive operations should be implemented.

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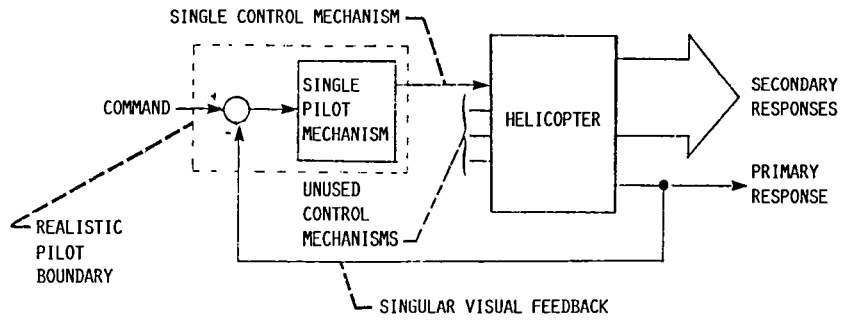


FIGURE 1. - BLOCK DIAGRAM OF SINGLE-VARIABLE PILOT MECHANISM WITHIN DOMINANT RESPONSE CONTROL LOOP.

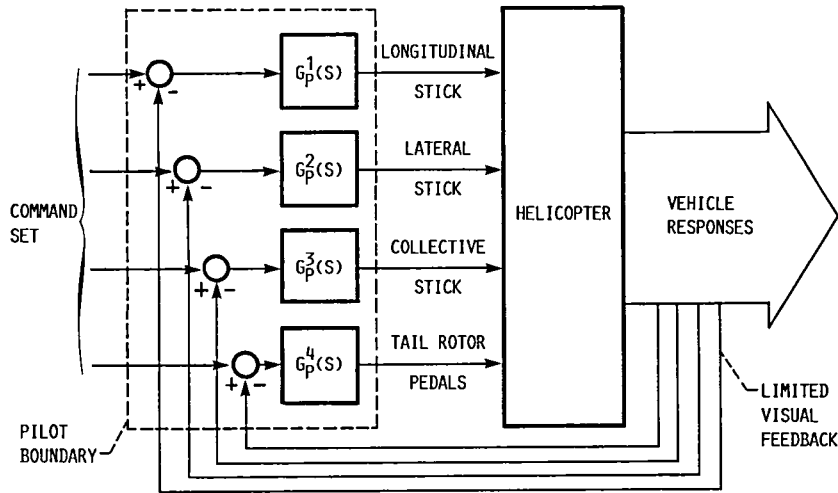


FIGURE 2. - BLOCK DIAGRAM OF MULTILoop CONTROL STRUCTURE.

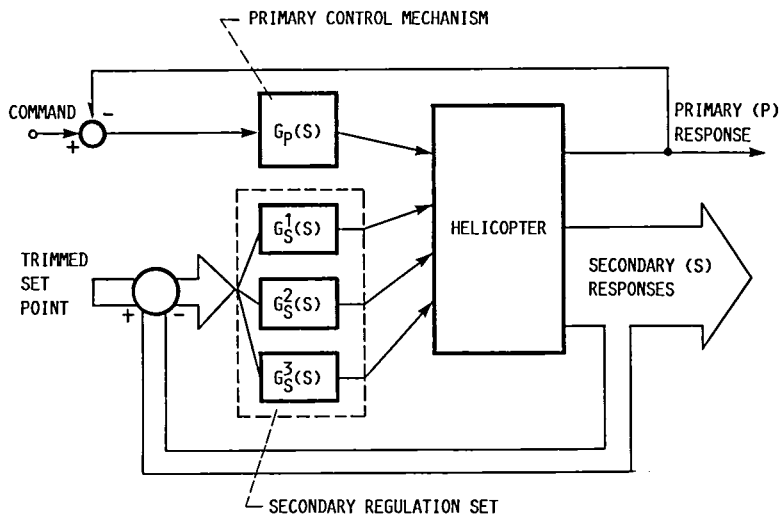
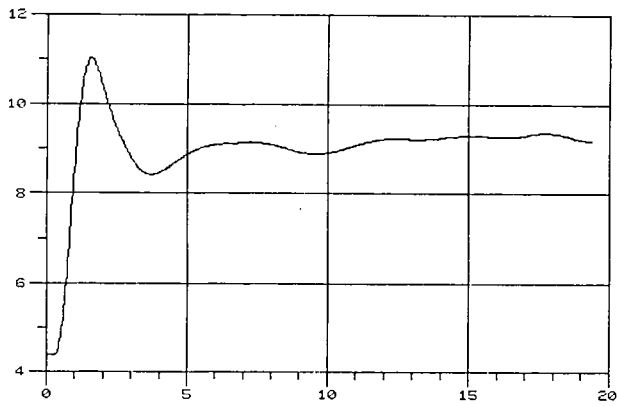
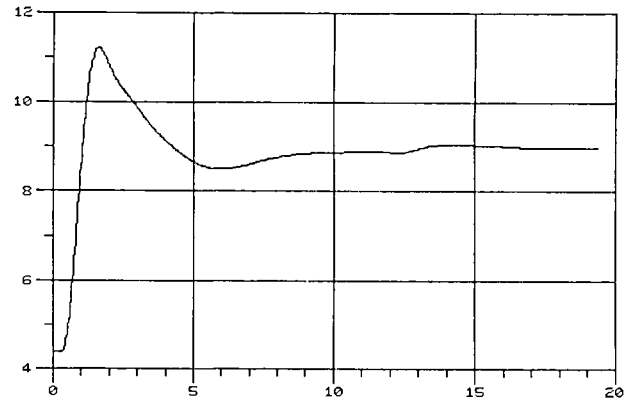


FIGURE 3. - BLOCK DIAGRAM OF STATIC CONFIGURATION FOR PRIMARY RESPONSE CONTROL.

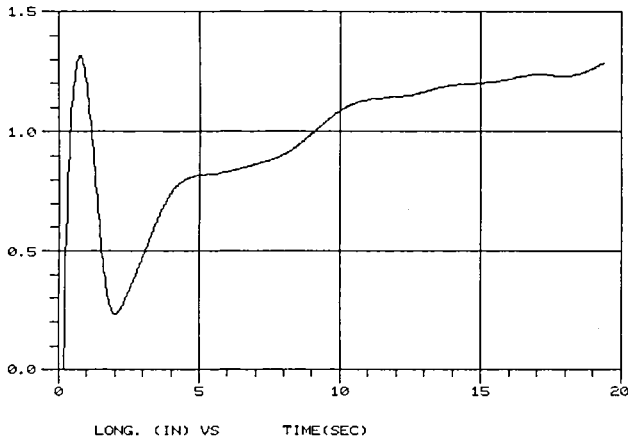


(A) MULTIVARIABLE.

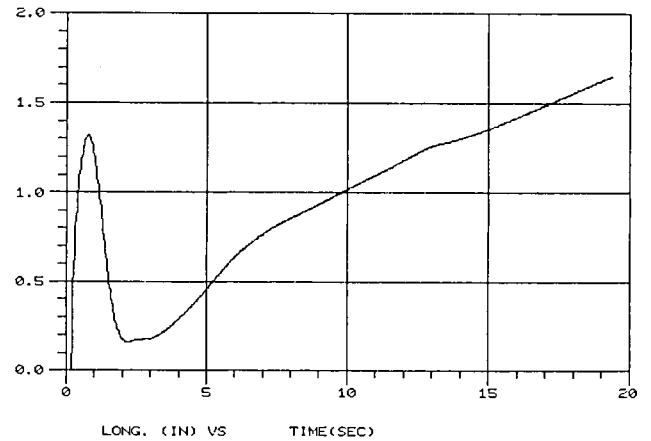


(B) SINGLE-VARIABLE.

FIGURE 4. - COMPARISON PLOT OF CLOSED-LOOP STEP RESPONSE OF PITCH CONTROL AT 80 KN.



(A) MULTIVARIABLE.



(B) SINGLE-VARIABLE.

FIGURE 5. - COMPARISON PLOT OF LONGITUDINAL CYCLIC-STICK DEFLECTION BY PILOT FOR PITCH MANEUVER.

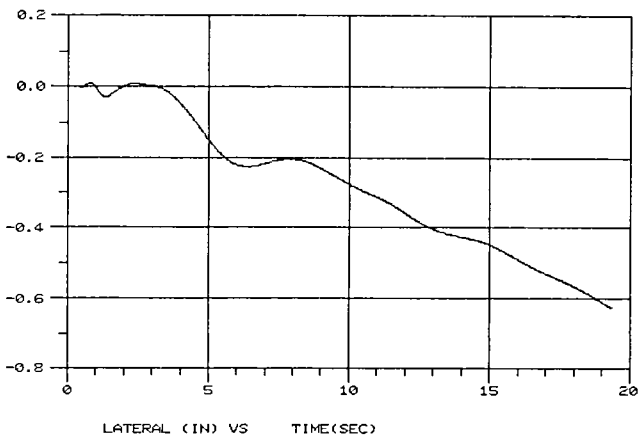


FIGURE 6. - LATERAL CYCLIC-STICK DEFLECTION BY MULTIVARIABLE PILOT TO MAINTAIN ROLL ANGLE REGULATION DURING PITCH MANEUVER.

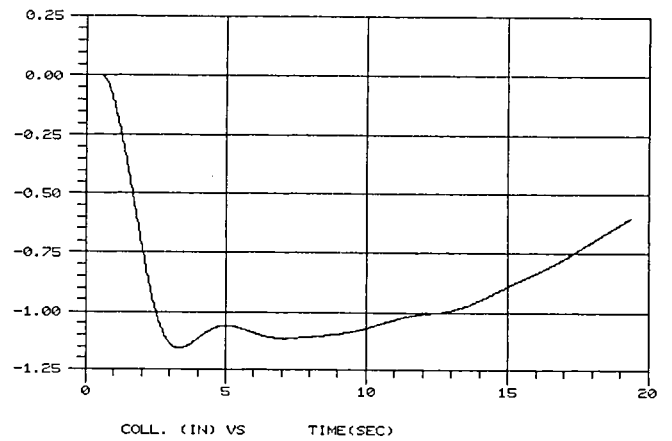


FIGURE 7. - MAIN ROTOR COLLECTIVE-STICK DEFLECTION BY MULTIVARIABLE PILOT TO MAINTAIN ALTITUDE REGULATION DURING PITCH MANEUVER.

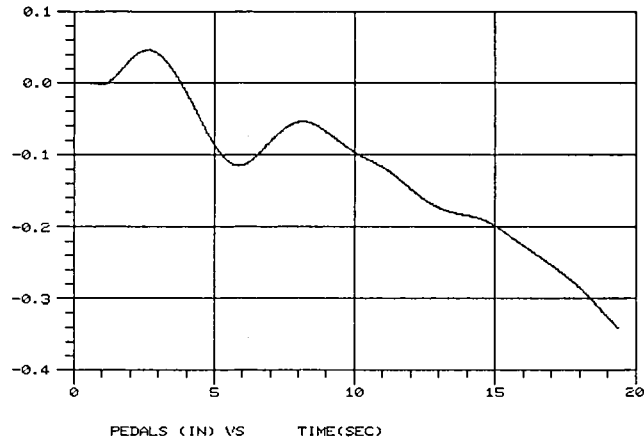
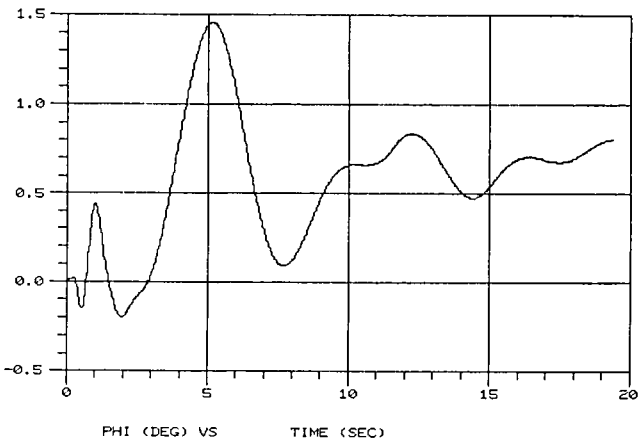
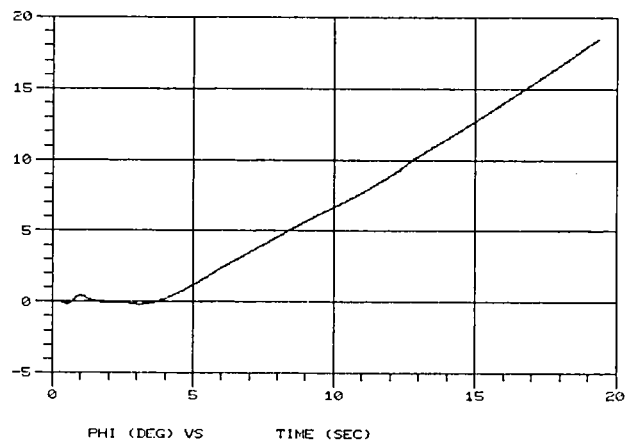


FIGURE 8. - TAIL ROTOR COLLECTIVE-PEDAL DEFLECTION BY MULTI-VARIABLE PILOT TO MAINTAIN HEADING REGULATION DURING PITCH MANEUVER.

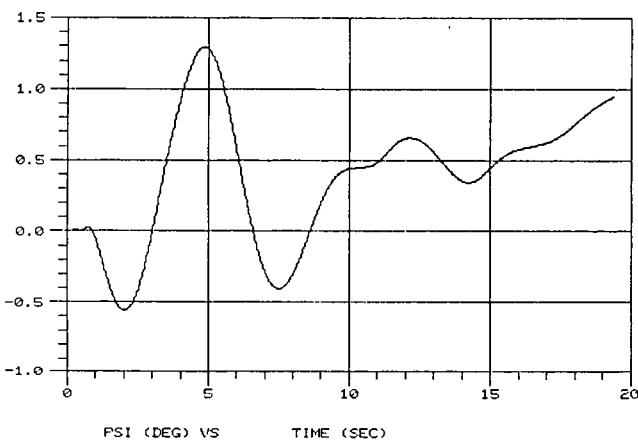


(A) MULTIVARIABLE PILOT.

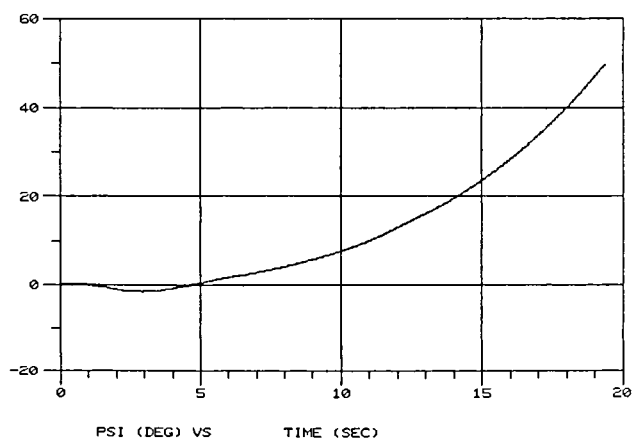


(B) SINGLE-VARIABLE PILOT.

FIGURE 9. - COMPARISON PLOT OF ROLL ANGLE RESPONSE TO PILOT DURING PITCH MANEUVER.

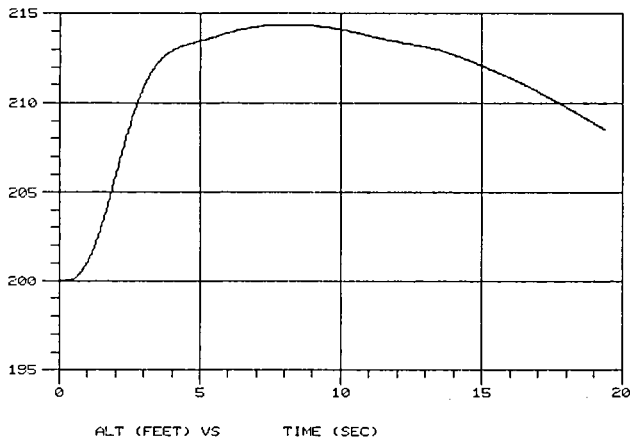


(A) MULTIVARIABLE PILOT.

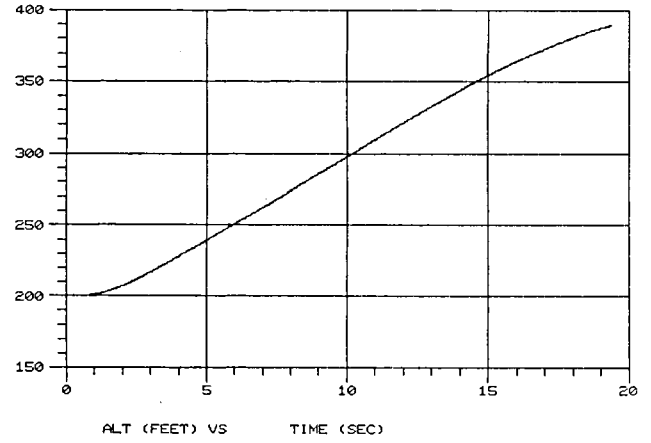


(B) SINGLE-VARIABLE PILOT.

FIGURE 10. - COMPARISON PLOT OF YAW ANGLE RESPONSE TO PILOT DURING PITCH MANEUVER.



(A) MULTIVARIABLE PILOT.



(B) SINGLE-VARIABLE PILOT.

FIGURE 11. - COMPARISON PLOT OF ALTITUDE POSITION RESPONSE TO PILOT DURING PITCH MANEUVER.

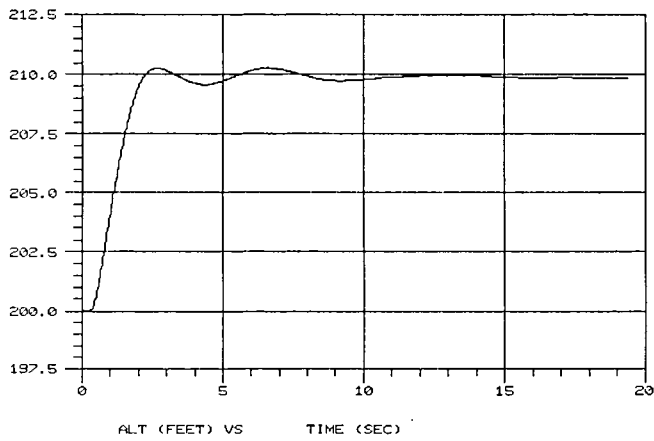


FIGURE 12. - CLOSED-LOOP STEP RESPONSE OF MULTIVARIABLE ALTITUDE CONTROL AT 80 KN.

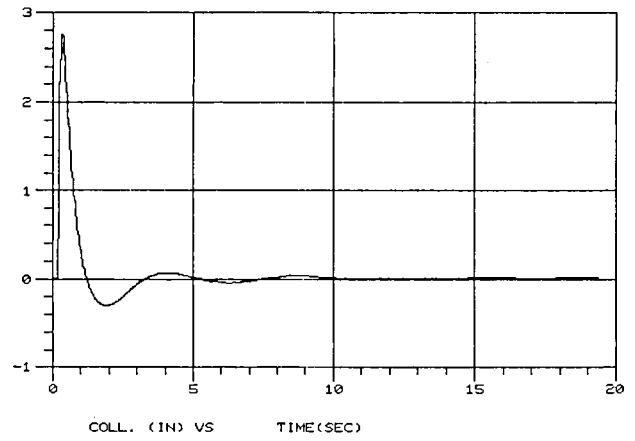


FIGURE 13. - MAIN ROTOR COLLECTIVE-STICK DEFLECTION BY MULTIVARIABLE PILOT TO PERFORM STEP MANEUVER.

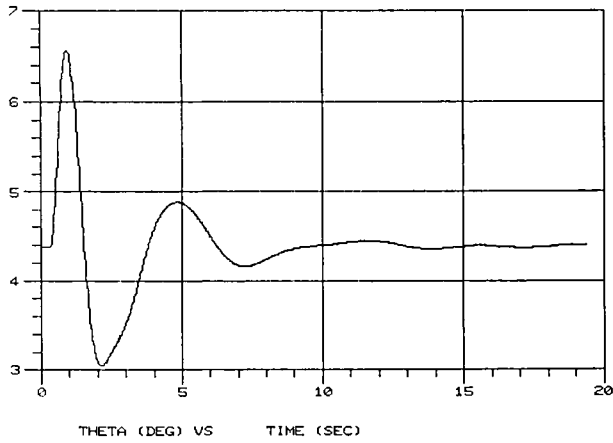


FIGURE 14. - REGULATED PITCH ANGLE REACTION TO ALTITUDE MANEUVER.

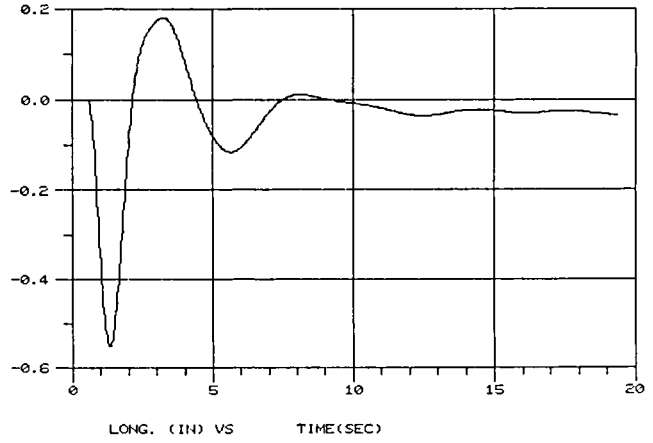


FIGURE 15. - LONGITUDINAL CYCLIC-STICK DEFLECTION BY MULTI-VARIABLE PILOT TO PROVIDE PITCH ANGLE REGULATION DURING ALTITUDE MANEUVER.

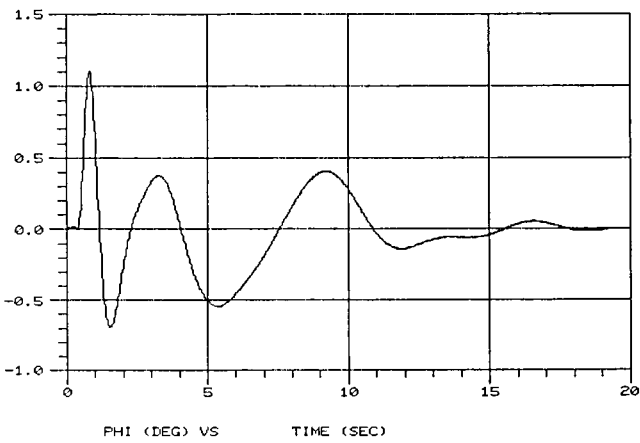


FIGURE 16. - REGULATED ROLL ANGLE REACTION TO ALTITUDE MANEUVER.

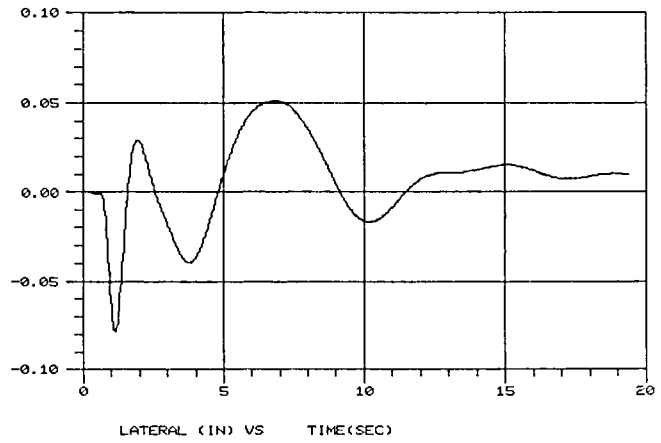


FIGURE 17. - LATERAL CYCLIC-STICK DEFLECTION BY MULTI-VARIABLE PILOT TO PROVIDE ROLL ANGLE REGULATION DURING ALTITUDE MANEUVER.

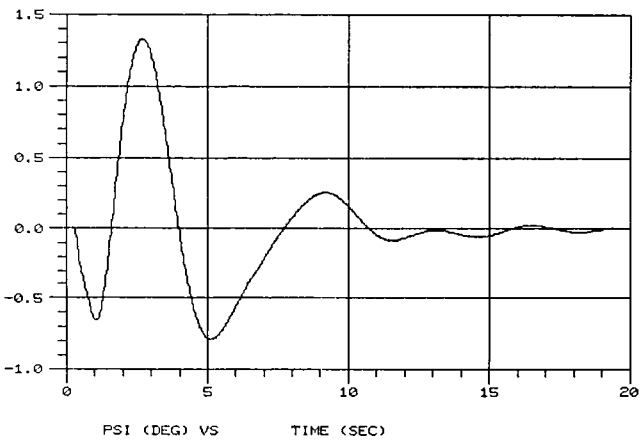


FIGURE 18. - REGULATED YAW ANGLE REACTION TO ALTITUDE MANEUVER.

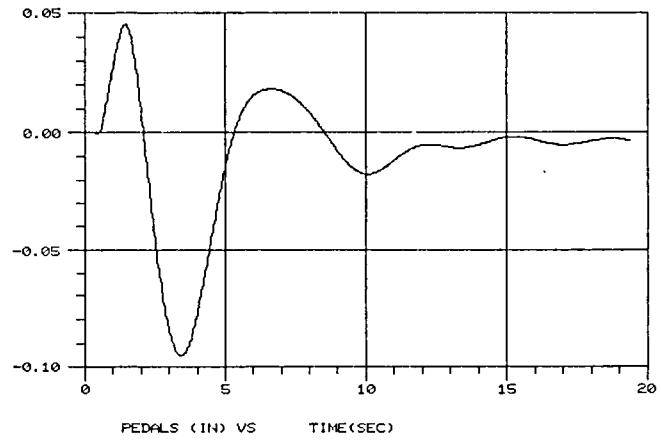


FIGURE 19. - TAIL ROTOR COLLECTIVE-STICK DEFLECTION BY MULTIVARIABLE PILOT TO PROVIDE YAW ANGLE REGULATION DURING ALTITUDE MANEUVER.

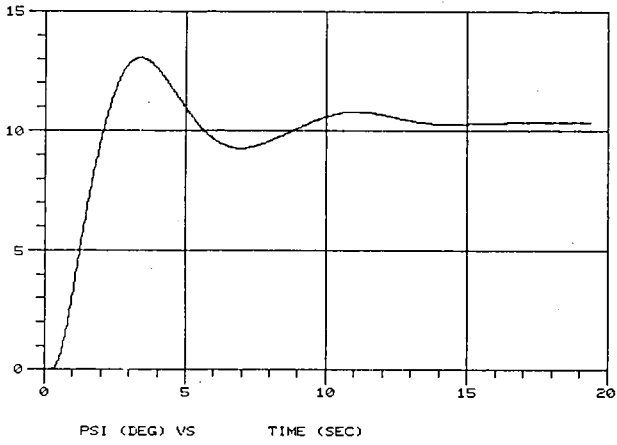


FIGURE 20. - CLOSED-LOOP STEP RESPONSE OF MULTIVARIABLE YAW CONTROL AT 80 KN.

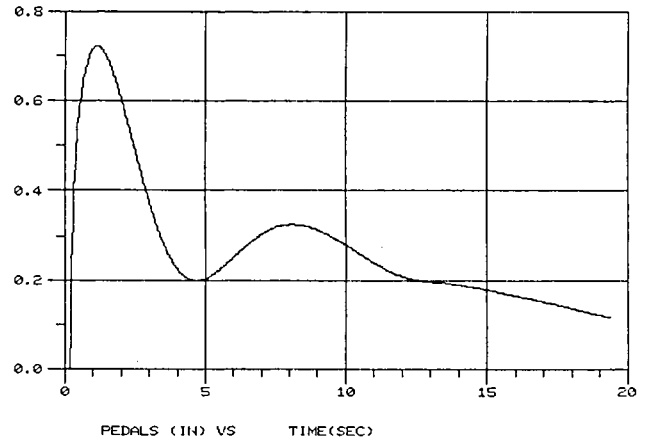


FIGURE 21. - TAIL ROTOR COLLECTIVE-PEDAL DEFLECTION BY MULTIVARIABLE PILOT TO PERFORM STEP MANEUVER.

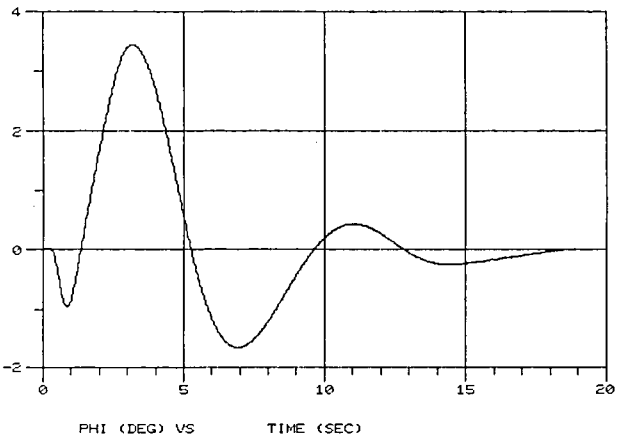


FIGURE 22. - REGULATED ROLL ANGLE REACTION TO YAW ANGLE MANEUVER.

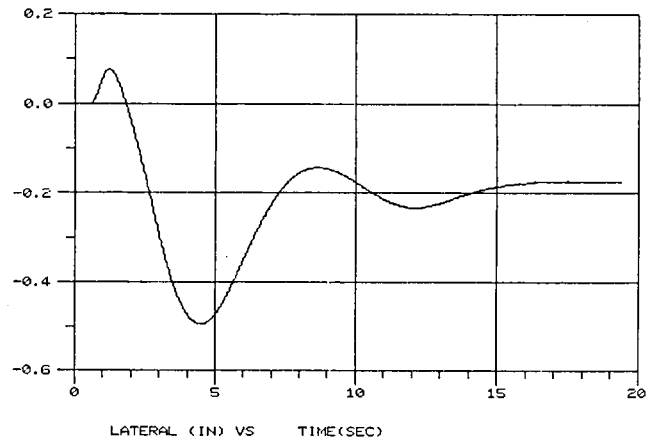


FIGURE 23. - LATERAL CYCLIC-STICK DEFLECTION BY MULTIVARIABLE PILOT TO PROVIDE ROLL ANGLE REGULATION DURING YAW ANGLE MANEUVER.

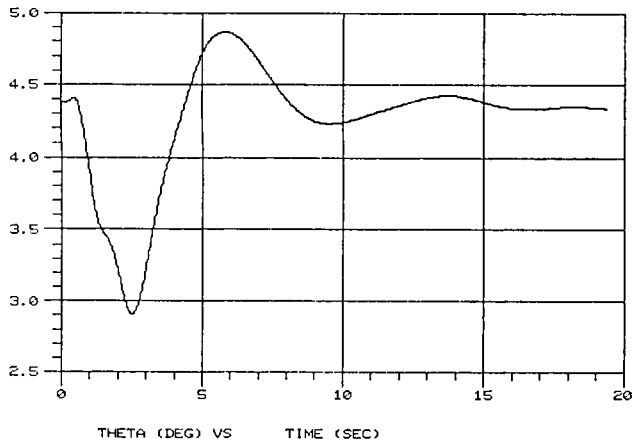


FIGURE 24. - REGULATED PITCH ANGLE REACTION TO YAW ANGLE MANEUVER.

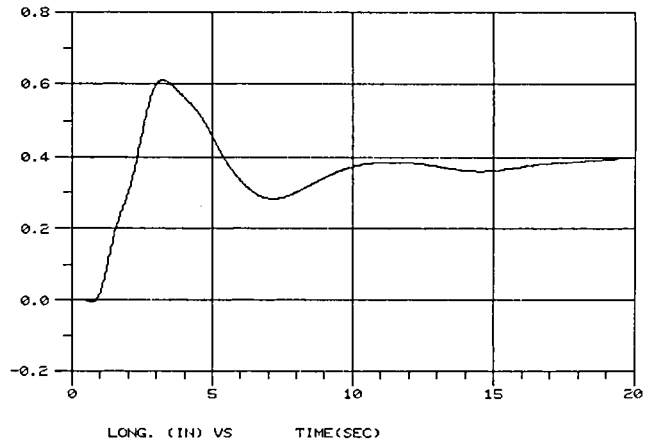


FIGURE 25. - LONGITUDINAL CYCLIC-STICK DEFLECTION BY MULTI-VARIABLE PILOT TO PROVIDE PITCH ANGLE REGULATION DURING YAW ANGLE MANEUVER.

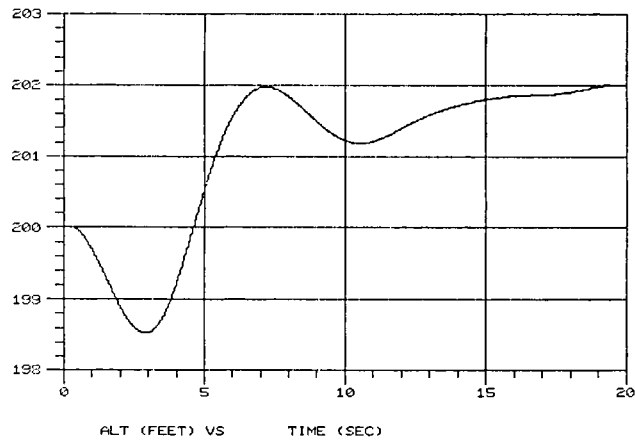


FIGURE 26. - REGULATED ALTITUDE REACTION TO YAW ANGLE MANEUVER.

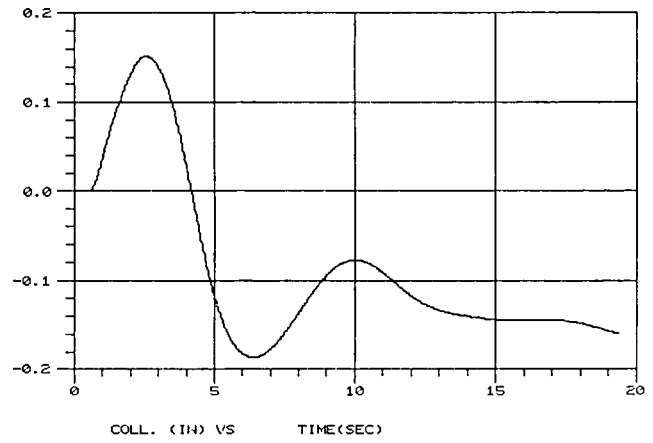


FIGURE 27. - MAIN ROTOR COLLECTIVE-STICK DEFLECTION BY MULTIVARIABLE PILOT TO PROVIDE ALTITUDE REGULATION DURING YAW ANGLE MANEUVER.

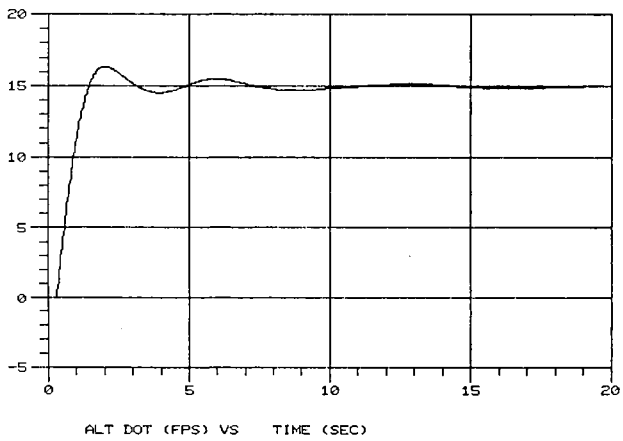


FIGURE 28. - CLOSED-LOOP STEP RESPONSE TO MULTIVARIABLE VERTICAL RATE CONTROL AT 60 KN.

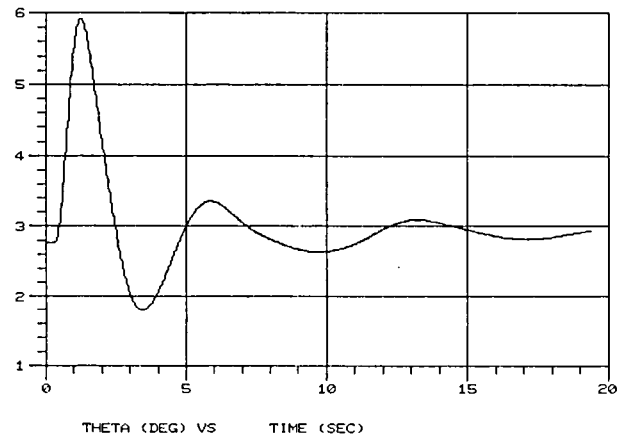


FIGURE 29. - REGULATED PITCH ANGLE REACTION TO VERTICAL RATE MANEUVER.

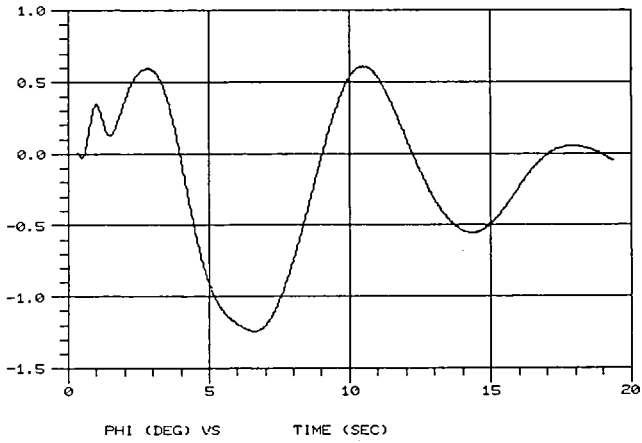


FIGURE 30. - REGULATED ROLL ANGLE REACTION TO VERTICAL RATE MANEUVER.

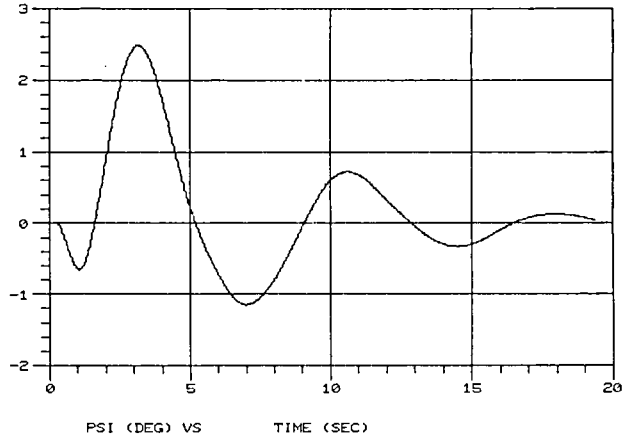


FIGURE 31. - REGULATED YAW ANGLE REACTION TO VERTICAL RATE MANEUVER.

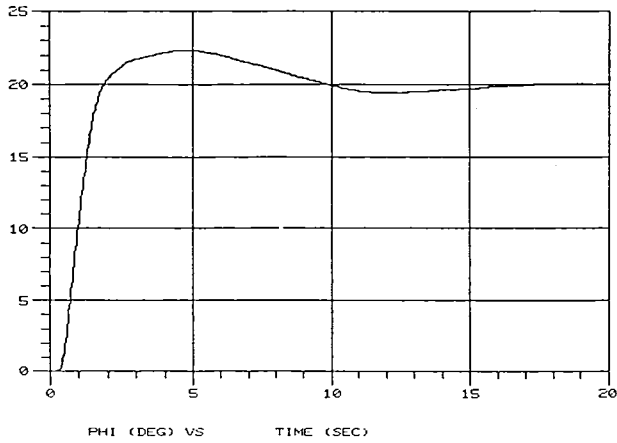


FIGURE 32. - CLOSED-LOOP STEP RESPONSE OF ROLL ANGLE DURING MULTIVARIABLE COORDINATED TURN MANEUVER AT 80 KN.

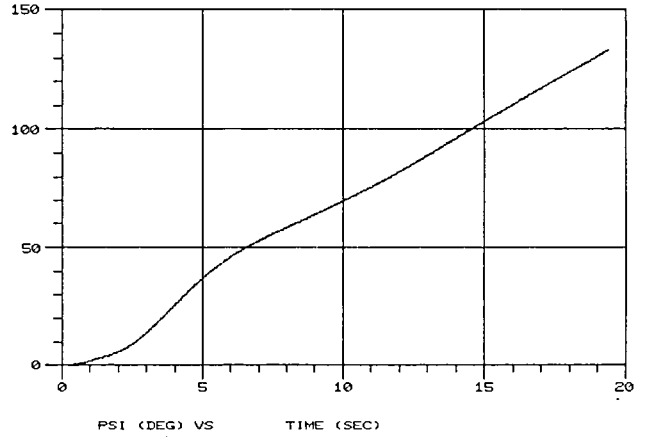


FIGURE 33. - HEADING REACTION DURING MULTIVARIABLE COORDINATED TURN.

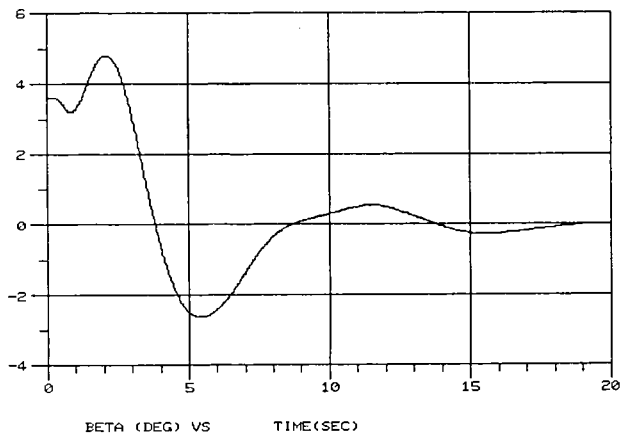


FIGURE 34. - REGULATED SIDESLIP ANGLE REACTION DURING COORDINATED TURN.

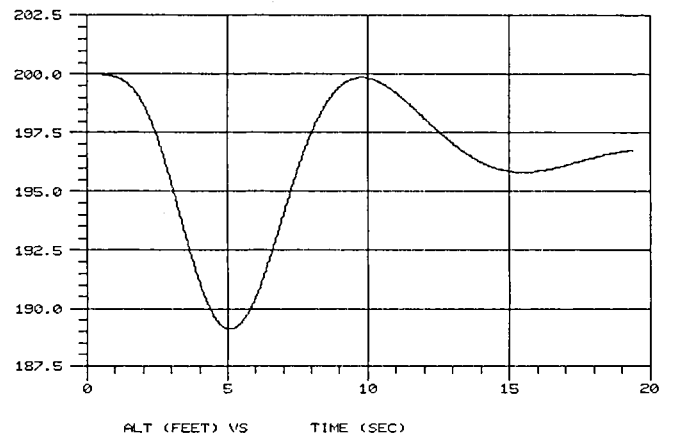


FIGURE 35. - REGULATED ALTITUDE REACTION DURING COORDINATED TURN.

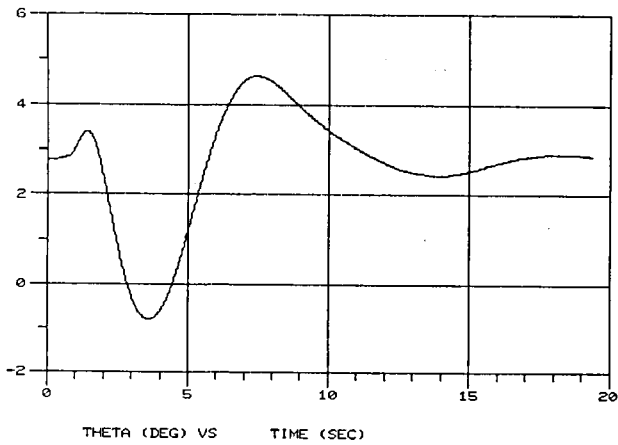


FIGURE 36. - REGULATED PITCH ANGLE REACTION DURING COORDINATED TURN.

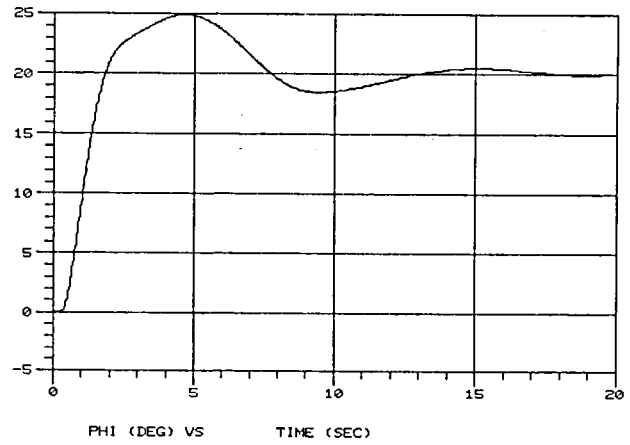


FIGURE 37. - CLOSED-LOOP STEP RESPONSE OF ROLL ANGLE DURING MULTIVARIABLE COORDINATED TURN MANEUVER AT 20 KN.

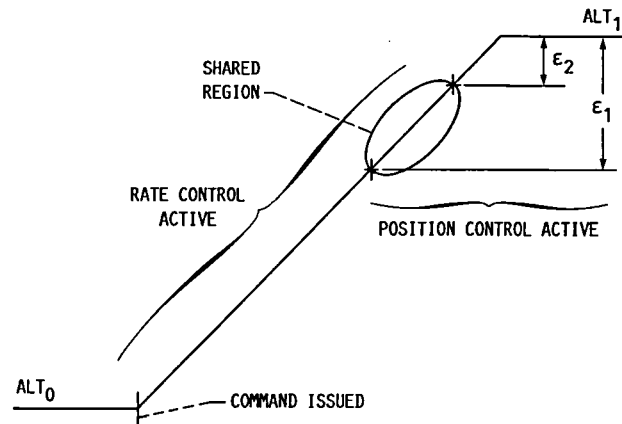


FIGURE 38. - ILLUSTRATION OF ALTITUDE MANEUVER REQUIRING DYNAMIC MODIFICATION OF FEEDBACK AND CONTROL STRUCTURE.

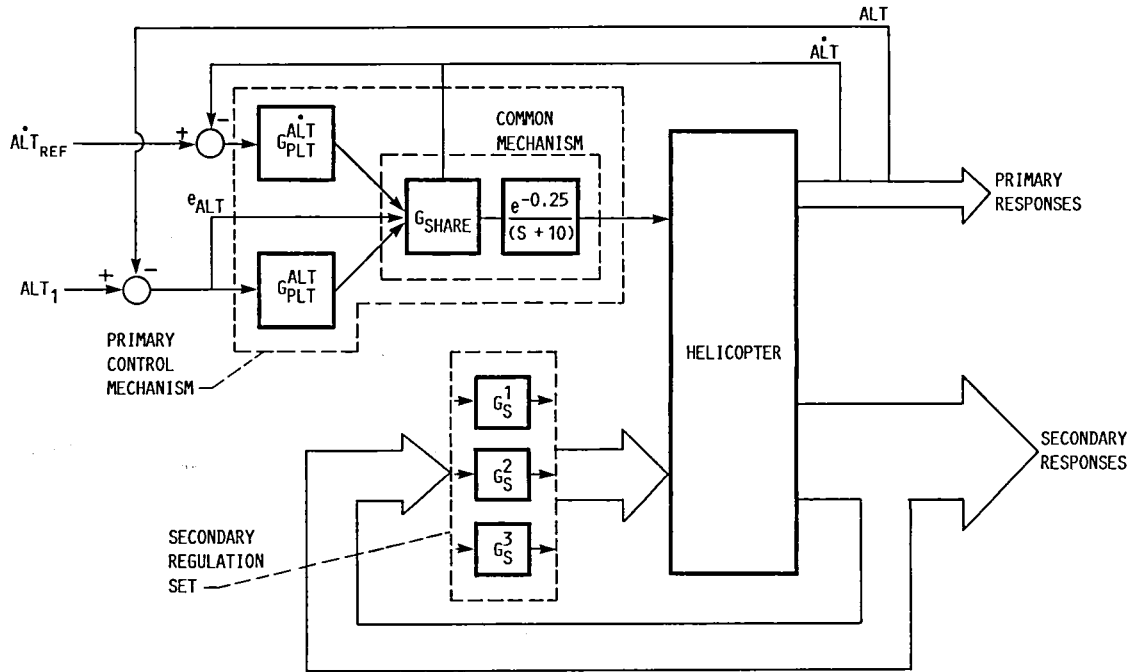


FIGURE 39. - BLOCK DIAGRAM OF DYNAMIC CONFIGURATION FOR ALTITUDE MANEUVERS.

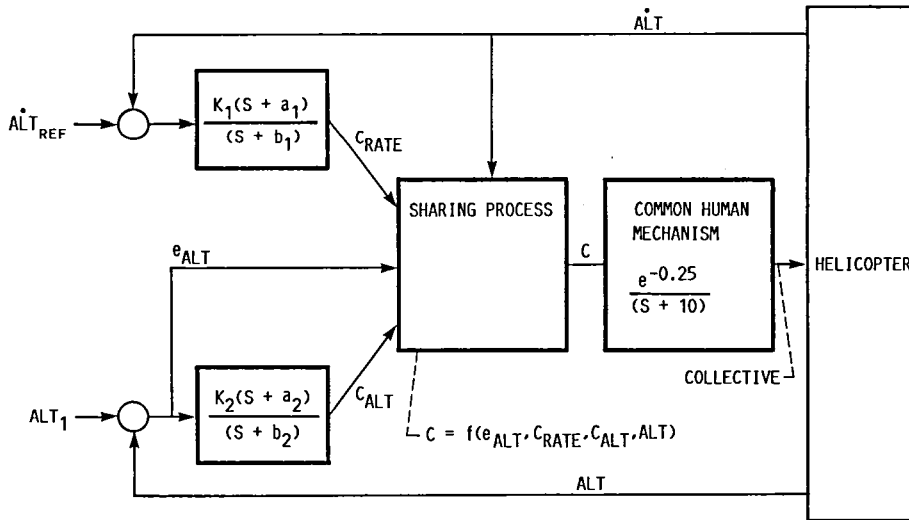


FIGURE 40. - BLOCK DIAGRAM OF INTERNAL STRUCTURE OF DYNAMIC ALTITUDE CONTROL CONFIGURATION.

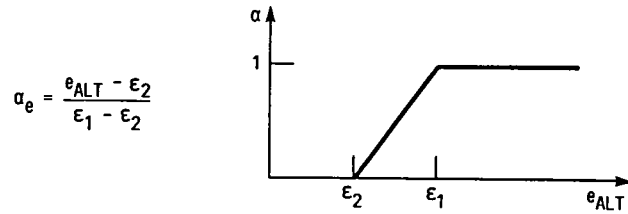


FIGURE 41. - ILLUSTRATION OF CONTROL AND FEEDBACK TRANSLATION AS FUNCTION OF ALTITUDE ERROR.

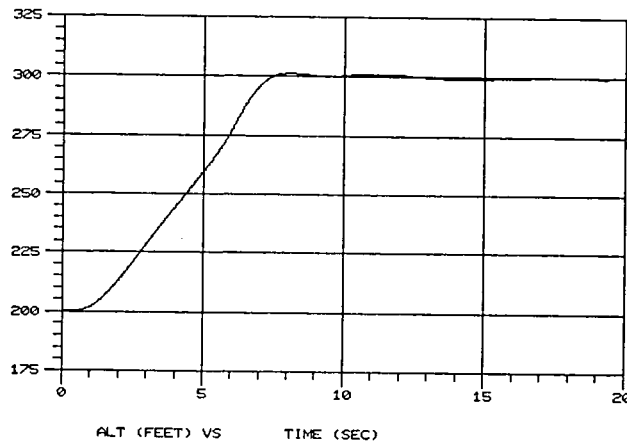


FIGURE 42. - TRANSLATIONAL ALTITUDE MANEUVER PERFORMED BY DYNAMIC ALTITUDE CONTROL CONFIGURATION.

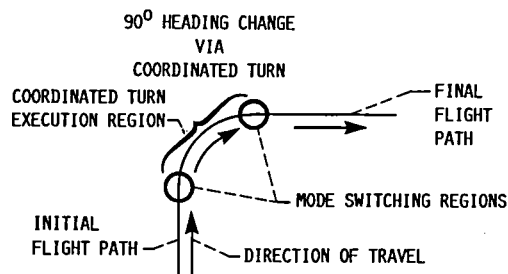


FIGURE 43. - ILLUSTRATION OF CONTROL CONFIGURATION REQUIREMENTS FOR EXECUTING COORDINATED TURNS.

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16. Abstract <p>This paper presents a computer simulation of a human response pilot model able to execute operational flight maneuvers and vehicle stabilization of a modern high-performance helicopter. Low-order, single-variable, human response mechanisms, integrated to form a multivariable pilot structure, provide a comprehensive operational control over the vehicle. Evaluations of the integrated pilot were performed by direct insertion into a nonlinear, total-force simulation environment provided by NASA Lewis. Comparisons between the integrated pilot structure and single-variable pilot mechanisms are presented. Static and dynamically alterable configurations of the pilot structure are introduced to simulate pilot activities during vehicle maneuvers. These configurations, in conjunction with higher level, decision-making processes, are considered for use where guidance and navigational procedures, operational mode transfers, and resource sharing are required.</p>					
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