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Phase II Piloted Simulation Study of Two Tilt-Wing Flap Control Concepts

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Nomenclature

AXP	Longitudinal pilot acceleration
ADI	Attitude direction indicator
b	Geared flap on the stick control gain
GF	Geared flap
GFB	Geared flap on the beep
GFS	Geared flap on the stick
K	Control gain
PIO	Pilot induced oscillation
PF	Programmed flap
q	Pitch rate
SAS	Stability Augmentation System
STOL	Short Takeoff and Landing
VASI	Visual Approach Slope Indicator
VMS	Vertical Motion Simulator
V/STOL	Vertical and Short Takeoff and Landing
i_w	Wing incidence
$\dot{i}_w$	Wing incidence rate
$\ddot{i}_w$	Wing incidence acceleration
δe	Elevator deflection
δf	Flap deflection
τ	Control system time constant
τ_{tj}	Control system (tail jet) time constant
θ	Pitch attitude

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Summary

A two phase piloted simulation study has been conducted in the Ames Vertical Motion Simulator to investigate alternative wing and flap controls for tilt-wing aircraft. This report documents the flying qualities results and findings of the second phase of the piloted simulation study and describes the simulated tilt-wing aircraft, the flap control concepts, the experiment design and the evaluation tasks. The initial phase of the study compared the flying qualities of both a conventional programmed flap and an innovative geared flap. The second phase of the study introduced an alternate method of pilot control for the geared flap and further studied the flying qualities of the programmed flap and two geared flap configurations. In general, the pilot ratings showed little variation between the programmed flap and the geared flap control concepts. Some differences between the two control concepts were noticed and are discussed in this report. The geared flap configurations had very similar results. Although the geared flap concept has the potential to reduce or eliminate the pitch control power requirements from a tail rotor or a tail thruster at low speeds and in hover, the results did not show reduced tail thruster pitch control power usage with the geared flap configurations compared to the programmed flap configuration. The addition of pitch attitude stabilization in the second phase of simulation study greatly enhanced the aircraft flying qualities compared to the first phase.

Introduction

Tilt-wings are a viable approach for Vertical and Short Takeoff and Landing (V/STOL) transports and other smaller V/STOL aircraft, because the tilt-wing concept lends itself well to reasonable efficiency in hover and to very good efficiency in cruise flight. A good technology base for tilt-wing aircraft exists. The first tilt-wing aircraft to transition from hover to forward flight was the Vertol VZ-2 in 1958. Other tilt-wing aircraft included the Hiller X-18 (1958-1964), the Vought-Hiller-Ryan XC-142 (1964-1967), and the Canadair CL-84 (1965-1974). In particular, the XC-142 and the CL-84 flew military operational demonstrations.

Some significant issues associated with tilt-wing aircraft include wing buffet during decelerating or descending flight, a strong wing angle to speed dependence, tilting system (wing, engine, and propellers) generated pitching moments, and the requirement for a tail rotor or tail thruster to provide pitch control at low speeds and hover.

Renewed interest in tilt-wing aircraft from the military and civil communities resulted in the piloted simulation study at Ames Research Center. This renewed interest includes use of tilt-wing aircraft for the U. S. Special Operations Command aircraft, the U. S. Air Force Advanced Theater Transport, NASA high speed rotorcraft studies, and proposed civil applications. A new look at tilt-wing aircraft was further motivated by advances in technologies such as propulsion, materials, and flight control systems which offer the potential to address shortfalls of previous tilt-wing aircraft.

Two piloted simulations of a transport size tilt-wing aircraft have been completed in the Ames Vertical Motion Simulator (refs. 1–4). This report documents the second simulation.

The initial simulation investigated the flying qualities of a conventional programmed flap (where the wing is driven directly) and an innovative geared flap (where the flap serves as an aerodynamic servo to position the free-pivoting wing). The programmed flap was the control concept used by previous tilt-wing aircraft. The geared flap was first proposed by Churchill (ref. 5) and has the potential to eliminate the tail rotor or tail thruster required by previous tilt-wing aircraft in hover and low speeds for pitch control; this could result in a significant reduction in aircraft weight and complexity. The objectives of the first simulation were to simulate a representative tilt-wing aircraft, to evaluate the flying qualities of the programmed flap and the geared flap, and to determine the feasibility of eliminating the tail rotor or tail thruster using the geared flap concept. The first simulation included development of a tilt-wing math model, and flying qualities evaluations of both control concepts. Also, results from this preliminary look at the geared flap concept indicated that the tail thruster pitch control requirements during hover and low speed were reduced with the geared flap configuration compared to the programmed flap configuration. And finally, since the flying qualities of both the programmed flap and the geared flap configurations were similar (generally in the level 2 range), the initial simulation showed that the geared flap concept might be feasible for tilt-wing aircraft.

In order to substantiate and extend the results of the initial simulation, a second simulation was conducted. The second simulation introduced several refinements, including a variation to the pilot control of the geared flap, a redefinition of the pilot evaluation tasks, and control law refinements. The objectives of the second simulation were to further evaluate the flying qualities of the programmed flap and geared flap control concepts, and to examine the pitch control requirements of both flap control concepts during hover and low speed flight.

This report describes the simulated tilt-wing aircraft, the flap control concepts, and the experiment design including the simulation facility and the pilot evaluation tasks. Second simulation results are documented, including flying qualities comparisons of the flap control concepts. A general discussion of control characteristics encountered with the geared flap configurations near hover and a discussion of the tail thruster control power usage by each configuration are included.

Co-author William Hindson was the project pilot. The authors wish to thank the other five evaluation pilots, Mr. Dorman Cannon, Mr. Ron Doeppner, Mr. Dan Dugan, Mr. Rick Simmons, and Mr. Mike Stortz. Special thanks to visiting pilots Mr. Joe Engle and Mr. Bob Fitzpatrick, to researchers Mr. Bill Decker and Ms. Laura Isler for their help before and during the simulation test, to Mr. Joseph Totah, and to pilot Ron Gerdes for his suggestions on the cockpit instrument panel and for his design of the wing and flap deflection indicator.

Simulated Tilt-Wing Aircraft

The conceptual tilt-wing aircraft of this study was a mid-sized V/STOL (vertical and short takeoff and landing) transport aircraft, about two-thirds the weight of a C-130. A tail thruster was included to provide pitch control during hover and at low speeds. A sketch of this conceptual aircraft is shown in figure 1. Table 1 lists many of the physical characteristics of the simulated aircraft.

Table 1. Physical characteristics of simulated aircraft

General	
Gross weight	87,000 lb
Overall length	92 ft
Payload	10,000 lb
Thrust/weight	1.15
Disk loading	40 psf
Wing loading	66 psf
Wing	
Span	109 ft
Area	1321 ft^2
Mean aerodynamic chord	12 ft
Tilt range	2°–105°
Tilt rates, geared to wing incidence	5°–10°/sec
Pivot, percent chord	41%
Flap	
Range	0°–60°
Propellers	
Diameter	26 ft
Horizontal tail	
Span	46 ft
Area	430 ft^2
Mean aerodynamic chord	9 ft
Tilt range, geared to wing incidence	0°–28°
Tail thruster	
Pitch control power	0.6 rad/sec^2

Aircraft Control Effectors

During hover and low speed flight, the pilots controlled longitudinal velocity and position using pitch attitude (tail thruster), wing incidence, or a combination of both. Pilot preference and choice of longitudinal control technique near hover was somewhat configuration dependent and will be discussed in the results. The throttle was used to control altitude during hover, low speed flight and conversion. During conversion, conventional control surfaces were phased in so that in airplane mode only conventional surfaces were used for flight control.

Simulation Math Model

The longitudinal rigid airframe aerodynamic and dynamic characteristics were modeled in detail. The aerodynamic model used a component buildup method to develop total forces and moments. Momentum theory was used to calculate propeller slipstream velocities which were then used with the "power-off" aerodynamics data to obtain "power-on" aerodynamic characteristics. Other elements in the math model included coupled-wing-body equations of motion, engine and propeller dynamics, programmed flap and geared flap controls with pitch attitude augmentation, a generic second-order landing gear model, a buffet boundary model, and a developmental ground effects model. The simulation model cycled real-time at a frame rate of 10 msec on a VAX 9000. A description of the math model may be found in reference 1.

Wing buffet is a significant issue for all tilt-wing aircraft during decelerating or descending flight. The buffet onset was defined from wind tunnel data and was a function of the effective wing angle-of-attack and the flap setting. The progressive deterioration of the flying qualities as deeper buffet was encountered was not modeled. A typical buffet boundary for the simulation is shown in figure 2 with respect to a glideslope of –7.5°. It should be noted that as tilt-wing aircraft transition from forward flight to hover, aerodynamic lift is replaced by powered lift and buffet onset becomes a ride quality issue. Recovery from buffet is immediate with the application of power.

The lateral/directional dynamic characteristics were modeled using stability derivatives. The dominant features were high roll damping and the addition of turn coordination above 30 knots. This study concentrated on longitudinal flying qualities, hence, accurate modeling of the lateral-directional dynamics was considered less critical to the study.

Flap Control Concepts

The programmed flap control concept uses a flap schedule that is a function of the wing incidence. The pilot sets a desired wing incidence by using the beeper switch located on the throttle grip which, in turn, sets the programmed flap deflection through cam or electrical control. The wing is driven directly by a hydraulic actuator, as shown in figure 3.

The geared flap control concept (ref. 5) uses the flap as an aerodynamic servo tab to control the wing incidence relative to the fuselage. A schematic of the geared flap control concept is shown in figure 4. The pilot input is through a beeper switch located on the throttle grip, or through a combination of the beeper switch and the longitudinal stick. Either way, the pilot input results in a flap deflection which in turn drives the wing incidence. The wing is essentially free pivoting (some damping is required) and is driven primarily by the forces generated by the flap deflections within the propeller slipstream. For example, an increase in flap deflection causes an unbalanced aerodynamic moment about the wing pivot which is balanced when the wing rotates down canceling the moment via mechanical feedback to the flap through the wing/flap linkage. Friction and artificial damping, as well as aerodynamic forces and moments generated by aircraft motion, also affect the pivoted wing response.

The programmed flap concept requires a tail rotor or tail thruster to provide pitch control in hover and at low speeds, since elevator effectiveness is not sufficient until higher velocities. Note on figure 5 that the upsetting aircraft pitching moments are caused by both the thrust and aerodynamic force offsets from the fuselage center of gravity as the wing tilts.

Using the geared flap concept, with the free-pivoting wing and the corresponding moment generating capability of the geared flap, the potential exists to eliminate the tail rotor or tail thruster (or at least to significantly reduce the pitch control power required from these auxiliary tail devices).

Simulation Experiment

Simulation Facility

The simulation was conducted on the Ames Vertical Motion Simulator (VMS). The VMS operational limits are ±22 ft of vertical motion and, depending on cab orientation, ±15 ft of longitudinal or lateral motion (ref. 6). Both simulations used the longitudinal orientation to focus on the longitudinal flying qualities of the aircraft. In the VMS the pilots can experience accelerations of up to ±22 ft/sec^2 vertically, ±13 ft/sec^2 longitudinally, and ±10 ft/sec^2 laterally. A sketch of the VMS is shown in figure 6.

Cockpit Layout

An interior layout of the cockpit is shown in figure 7. Several instruments were arranged differently than in the first simulation at the pilots' request. Glideslope and localizer information were added for this simulation and were displayed around the attitude direction indicator (ADI). A new instrument was also added for this simulation which combined both wing incidence and flap deflection information. In addition to the analog instruments, this simulation displayed both wing incidence and speed digitally. The cockpit control effectors consisted of a center stick with a trim button, a left-hand throttle with a spring return rotary beep switch, and rudder pedals. A seat shaker and an angle-of-attack warning light were installed to cue the pilot when buffet was encountered.

Three windows, arranged center, right, and lower right, provided the external computer-generated view of an airport environment with a 10,000 ft runway. The CT5A visual system used in this simulation was a generation newer than the visual system used in the first simulation and had many features that enhanced the overall image quality.

Study Configurations

Three flap configurations were evaluated by the pilots; these were programmed flap (PF), and two geared flap configurations. In the first geared flap configuration the pilots controlled the geared flap with the beeper switch located on the throttle grip. This configuration was the same as the geared flap configuration evaluated in the initial simulation and was called geared flap on the beep (GFB). In the other geared flap configuration the pilots controlled the geared flap partially through the beeper switch on the throttle and partially through the longitudinal stick. This configuration was called geared flap on the stick (GFS).

Control diagrams for the PF, GFB, and GFS configurations are shown in figures 8, 10, and 11, respectively. Gain values, limits, and look-up tables for these control diagrams are reported in appendix A (table A-1, and figs. A-1–A-3). All three flap configurations used the spring return rotary beep switch embedded on the throttle grip to control the wing tilting mechanism. Release of the beep switch resulted in a constant value of the last resulting wing incidence. In the PF configuration (fig. 8) the pilot beep switch input generated a wing rate command, and the flap deflection was programmed to the resulting wing incidence through the wing/flap schedule, shown in figure 9. In the GFB configuration (fig. 10) the pilot beep switch input generated a reference (desired) wing incidence which through the control laws then resulted in a flap setting that drove the wing incidence towards the reference wing incidence. In the GFS configuration (fig. 11) the pilot beep switch input and the longitudinal stick input were combined to generate a reference wing incidence which then resulted in a flap setting that drove the wing incidence towards the desired wing incidence. For the latter configuration the pilot had full authority of wing tilt on the beep switch and a limited authority on the longitudinal stick. The stick authority translated to about 2° of wing per inch of longitudinal stick for wing incidences of 25°–105° and was scheduled from 2°–0° for wing incidences less than 25°. It should be noted that with no longitudinal stick activity, the GFB and the GFS configurations yield the same aircraft characteristics.

Evaluation Tasks

The evaluation tasks were redefined for this simulation to emphasize the flying qualities differences among the flap configurations during conversion and hover. The baseline altitude was chosen at 70 ft to avoid configuration-specific ground effects and because 70 ft was considered a reasonable reference altitude for the large simulated aircraft. The tasks were bounded by specific performance standards, thereby permitting a better application of the Cooper-Harper pilot rating method (ref. 7). The four tasks, shown in figure 12, and their performance standards are described below.

Hover Station Keeping with Turbulence

The aircraft was positioned over a predetermined location on the runway at 70 ft altitude in hover. The turbulence level was 8 ft/sec rms in all three axes. The pilot attempted to maintain position for 70 sec, using whatever technique he preferred (wing incidence, pitch attitude adjustment, or a combination of the two). The performance standards are listed in table 2.

Table 2. Performance standards for hover station keeping with turbulence task

Parameter	Desired	Adequate
Altitude	±10 ft	±20 ft
Longitudinal position	±25 ft	±50 ft
Lateral position	±25 ft	±50 ft
Heading	±10°	±15°

Level Inbound Transition to Hover

The aircraft was positioned initially 2,000 ft short of the runway threshold at 70 ft altitude with 93 knots velocity. This initial velocity corresponded to 9° of wing angle in the programmed flap configuration and to 16° of wing angle in the geared flap configurations (for the same velocity, the wing angles are different because of different flap settings). The pilots decelerated the aircraft to arrive at a hover over the designated end position (3,130 ft down the runway) while trying to maintain 70 ft altitude, level pitch attitude, and avoiding buffet. The pilots were allowed to use whatever wing tilt rate they preferred. The performance standards are listed in table 3. The buffet time shown in tables 3–5 represents the total accumulated buffet time.

Table 3. Performance standards for level inbound transition to hover task

Parameter	Desired	Adequate
Altitude	±10 ft	±20 ft
Pitch attitude	±2°	±4°
Heading	±5°	±10°
Lateral position	±10 ft	±20 ft
Buffet (total time)	≤ 3 sec	>3 sec

Descending Decelerating Inbound Transition to Hover

The aircraft was positioned initially 6,000 ft short of the runway at 800 ft altitude. The initial wing incidence (46° for programmed flap configuration and 52° for the geared flap configurations) was selected to yield a speed of 40 knots, hence investigating only the final stages of deceleration where buffet considerations were minimized (see fig. 2) and where differences among the control configurations were maximized. The pilots captured the –7.5° glideslope using both electronic guidance (glideslope and localizer guidance on the ADI) and the visual approach slope indicator (VASI) lights on the runway, and established a nominal sink rate of 550 ft/min. At 400 ft altitude, the wing incidence was increased to decelerate, and power was added as necessary to remain on the flightpath. The pilots decelerated the aircraft to a hover at 70 ft altitude over the designated end position (562 ft down the runway) while maintaining level pitch attitude and avoiding an overshoot of the final end position. The pilots were to avoid buffet as much as possible by using low deceleration rates and by avoiding low power settings. The performance standards are listed in table 4. The word "dot" used in table 4 refers to the glideslope guidance markers on the ADI.

Longitudinal Reposition

The aircraft was positioned initially 700 ft short of the runway threshold at 70 ft altitude in hover. The pilots began a forward translation, achieving a wing angle that was 40° less than the initial wing angle at hover, then started decelerating to a hover, and ended the task in hover at 70 ft altitude over the designated end position, 1,200 ft down the runway. The pilots were to maintain 70 ft altitude and level attitude, avoid buffet, and arrive at the end position without overshoot. The performance standards are listed in table 5.

Table 4. Performance standards for descending decelerating inbound transition to hover task

Parameter	Desired	Adequate
Glidepath (<200 ft)	±1/2 dot	±1 dot
Glidepath (>200 ft)	±1 dot	±1 dot
Altitude (lowest limit)	60 ft	50 ft
Pitch attitude	±2°	±4°
Heading	±5°	±10°
Buffet (total time)	≤ 5 sec	>5 sec
Overshoot (of hover position)	none	1

Table 5. Performance standards for longitudinal reposition task

Parameter	Desired	Adequate
Altitude	±10 ft	±20 ft
Pitch attitude	±2°	±4°
Heading	±5°	±10°
Overshoot (of hover position)	none	1
Buffet (total time)	≤ 3 sec	>3 sec

Task Environment and Visual Cues

The tasks were evaluated in daytime calm conditions with the exception of the hover station-keeping task which included turbulence. The tasks were performed visually, except for the descending decelerating transition to hover, which could be performed both visually and with the aid of the glideslope and localizer information displayed on the ADI.

Visual cues were important to all the tasks. In addition to an improved visual system, several visual cues were added to aid the pilots. VASI lights were used to help the pilots maintain the –7.5° glideslope during approach. Runway cracks and tire marks were added to aid in depth perception and to add realism. Several vertical pylons consisting of stacked color-coded 10 ft cubes were added along the edge of the runway to provide height information. STOL runway markings were superimposed over the main runway. The STOL runway markings were used to define task end positions. Task end positions were also marked by a truck or an arresting gear on the right side of the runway where they were easily seen from the lower right cockpit window (chin window).

Evaluation Procedure

All evaluation pilots attended a briefing before flying the simulator where they were introduced to general tilt-wing aircraft characteristics. At the briefing they also received a handout which included aircraft and simulator familiarization tasks, evaluation task definitions, performance standards, a Cooper-Harper rating scale card (from ref. 7) and a list of topics to comment on before rating the configurations.

The pilots were allowed as much time as they needed to familiarize themselves with the aircraft and the simulator before evaluating the tasks. During the evaluation runs the pilots were encouraged to give comments as they performed the task. Before enunciating their decisions through the rating scale card the pilots were required to comment on specific aircraft characteristics, perceived task performance, and pilot workload.

Pilots were allowed to give half ratings between 1-3, 4-6, and 7-9. Use of 3.5 , 6.5, and 9.5 was not allowed because they represent important boundary conditions.

Evaluation Pilots

All six evaluation pilots had extensive experience with fixed wing aircraft and helicopters; five also had powered-lift aircraft experience. Four pilots had experience flying the XV-15 tiltrotor; one of these pilots also had experience flying the V-22 tiltrotor. One pilot also had experience flying the CL-84 tilt-wing.

Results

This section begins with a discussion on pitch axis stabilization improvements made during this simulation and is followed by a discussion of a transient response characteristic of the geared flap configurations near hover. This is followed by flying qualities comparisons of the flap configurations during each evaluation task and by a discussion of the tail thruster control power usage by each flap configuration. Representative time histories of all evaluation tasks are included in appendix B, and a listing of the pilot ratings and comments is included in appendix C.

Pitch axis stabilization was augmented in rate only during the initial simulation and rate plus attitude during this simulation, as shown in figure 13. Attitude augmentation was an improvement which greatly alleviated the pilot pitch axis control workload. This effect can be seen in the pitch activity in figure 14. With the addition of pitch attitude stabilization in this simulation, the pilots were allowed to direct their full attention to longitudinal maneuvers through wing control, and hence, they rarely commented on pitch axis control problems.

During hover, the initial response of the geared flap configurations to a forward wing command was a longitudinal aircraft acceleration transient in the rearward direction. The initial rearward acceleration was the result of a transient increase in force (lift) on the wing caused by the initial flap deflection in the propeller slipstream. This characteristic of the geared flap configurations resulted in a delay in the longitudinal velocity response which led to degraded velocity and position predictability near hover. The acceleration transient was reduced by the addition of damping about the wing pivot in this simulation, as comparisons of figure 15(a) and (b) show. With the addition of damping, the longitudinal response was felt as more of a hesitation than a reversal.

Figure 15 shows time histories during transitions from hover (using beep inputs) for three geared flap configurations and a programmed flap configuration. Figure 15(a) is a time history from the first simulation and figure 15(b)–(d) are time histories from the second simulation. The flap activity and rearward pilot longitudinal acceleration (AXP) for the geared flap may be seen in figures 15(a)–(c), but particularly in figure 15(a) where there is no damping about the wing pivot. By comparison, figure 15(d) for the programmed flap does not show any rearward pilot acceleration. Figures 15(b) and (c) show the similar aircraft characteristics of the geared flap configurations when no longitudinal stick is used with the GFS configuration.

Pilot compensation and workload comments in this report are based on the pilot comments (documented in appendix C). Pilot performance (desired or adequate, as defined in tables 2–5) was measured during evaluation runs; hence, comments on task performance are based on recorded data and not on pilot comments.

Hover Station Keeping with Turbulence

The flying qualities pilot evaluations for this task are summarized in figure 16 for each flap configuration. Representative time histories are included in appendix B, figures B-1–B-8.

As mentioned in the task definition, the pilots were allowed to use whatever technique they preferred (wing incidence, pitch attitude, or a combination of the two) to regulate longitudinal position in hover. To control longitudinal positioning with the PF configuration, three pilots used wing incidence (wing beep), two pilots used pitch attitude (longitudinal stick), and one pilot used both wing incidence and pitch attitude. The CL-84 pilots had a preference for the wing incidence technique. "For forward and aft translation the pilots preferred to use wing tilt while holding the fuselage level. This was smoother, easier and more natural than tilting the whole aircraft" (ref. 8).

With both GF configurations most pilots preferred using pitch attitude over wing incidence to control longitudinal positioning. With the GFB configuration, five pilots used pitch attitude and one used wing incidence for longitudinal positioning. With the GFS configuration, five pilots used pitch attitude and one used wing incidence for longitudinal positioning (with this configuration the pitch attitude technique also affected the wing incidence, since the longitudinal stick had some wing tilting authority).

One pilot evaluated this task with the GFB configuration using both longitudinal positioning techniques and rated the pitch attitude technique a 5 and the wing incidence technique a 7, where the degradation was primarily attributed to a delay in longitudinal response leading to oscillatory longitudinal characteristics. This delay stems from the characteristic of the GF configurations mentioned earlier, where the initial response to a forward wing command results in a rearward acceleration transient. This response characteristic led most pilots to control position through attitude, but as one pilot noted the pitch attitude technique would not be acceptable for such a large aircraft, "... the pitch activity would certainly be disconcerting to passengers." This response characteristic was also responsible for degraded speed predictability near hover with the GF configurations compared to the PF configuration.

Another pilot evaluated this task with the GFB configuration on three separate runs: one with turbulence in all three axes, one with no lateral turbulence, and one with no turbulence. The pilot flying qualities ratings were 3, 2.5, and 1.5, respectively.

One hypothesis concerning the GFS configuration has been that it would reduce pitch control requirements and hence, pitch activity might be lower than with the GFB configuration. In general, examination of data did not show reduced pitch activity compared to the GFB configuration. This is probably due to the current level of control law development which allowed insufficient wing authority on the longitudinal stick (about 2°/inch). However, one pilot using the longitudinal stick (pitch attitude technique) with all three flap configurations showed the lowest pitch activity with the GFS configuration (compare figs. B-6–B-8).

In general, the workload and pilot compensation associated with height and position control with both GF configurations were similar to the PF configuration, except that the lag between wing movement and perceptible longitudinal aircraft response required moderate to considerable lead compensation. While hovering with the PF configuration, one pilot noted that controlling altitude while trying to maintain position was a highly iterative process, "... constantly beeping (moving) the wing for longitudinal control" while at the same time, "using multiple throttle inputs to control altitude."

In general, the pilots achieved desired performance standards for altitude, lateral position, and heading, but adequate performance for longitudinal position. Averaged longitudinal drifts were –14 ft to 51 ft with the PF, –13 ft to 38 ft with the GFB, and -5 ft to 38 ft with the GFS. In most cases the pilots were unable to perceive the longitudinal drift because of limited visual cues.

Level Inbound Transition to Hover

The flying qualities pilot evaluations for this task are summarized in figure 17 for each flap configuration. Representative time histories are included in appendix B, figures B-9–B-11.

At low wing incidence, the short term response to wing movements was an aircraft heave response with all configurations. Some pilots felt that the heave response to initial wing change was reduced with the GFB configuration compared to the PF configuration; one pilot noted that the "heave response to initial beep (wing tilt) was much better than (the) programmed flap, coupling (was) not as bad." Another pilot felt the throttle usage to control the heave response was lower with the GFB configurations and thus an "improvement over the programmed flap." The heave response with the GFS configuration was similar to the GFB configuration.

The aircraft heave response to wing changes is a typical tilt-wing response during decelerating flight as the following excerpt (ref. 9) about the CL-84 explains. "In order to decelerate, the wing tilt angle must be increased, and the thrust reduced to prevent ballooning (heave). As the speed reduces, the thrust-power required increases. Thus, the pilot must find the matching rates of wing tilt angle and power increases to perform a smooth, level deceleration."

All pilots agreed that the time spent in buffet increased with the GFB and the GFS configurations compared to the PF configuration (an average total buffet time of 8.0 sec for the GFB and 8.4 sec for the GFS vs. 2.1 sec for the PF). The increased time spent in buffet with the GF configurations is most likely due to lower flap settings than the PF configuration for similar wing angles. Examination of time histories showed that buffet was encountered during the mid-wing-incidence range of 35°–60° for both the PF and the GFB configurations. When operating in this mid-wing-incidence range, the flap range was 20°–40° for the PF and 5°–20° for the GFB. Increase in leading and trailing edge flap deflections on the CL-84-1 improved the buffet boundary of the aircraft (ref. 10). Also, one of the methods to alleviate buffet proposed from results of flight investigations of the VZ-2 was larger flap deflections (ref. 11).

With the PF configuration, the final hover acquisition was accomplished by some pilots by overcontrolling wing position to achieve zero speed more quickly and then resetting the wing incidence required for hover. To avoid the degraded predictability of speed and position typical of the GF configurations near hover when using the wing for longitudinal positioning, some pilots accomplished the final hover acquisition by establishing the hover wing incidence early and then using pitch attitude for final position capture.

Power management was required by the pilots to offset the heave response to a wing change and to avoid buffet (especially with both GF configurations). Pilot compensation was also required to better predict attaining the hover end position.

In general, the pilots achieved desired performance for altitude, pitch attitude, heading, and lateral position with all three flap configurations, desired performance for buffet with the PF configuration, but only adequate performance for buffet with both GF configurations.

Descending Decelerating Inbound Transition to Hover

The flying qualities pilot evaluations for this task are summarized in figure 18 for each flap configuration. Representative time histories are included in appendix B, figures B-12–B-15.

The task definition was such that beginning at 400 ft, deceleration could be accomplished slowly and smoothly with slow monotonic wing and power increases to maintain glideslope. In these circumstances, the differences among the three flap configurations were minimal.

Most pilots felt the workload was low because the task was slow and glideslope control only required power changes. However, with the PF configuration, two pilots noticed a coupling between wing movement and vertical response and felt that the workload was high due to poor heave predictability. Examination of time histories showed that the reported heave control difficulties were associated with large abrupt wing movements.

With the GF configuration one pilot noted that he "felt glideslope tracking was the tightest so far" compared to the other two flap configurations; another pilot said "height control was easier than with the PF configuration." Since the task definition required a level pitch attitude, longitudinal stick activity was minimal, and the GFS configuration showed only subtle differences from the GFB configuration.

The final hover acquisition technique used by some pilots was again somewhat configuration dependent, as discussed in the previous task.

Largely because of the task definition, no buffet was encountered with any of the flap configurations. In general, the pilots achieved all the desired performance standards with all three flap configurations.

Longitudinal Reposition

The flying qualities pilot evaluations for this task are summarized in figure 19 for each flap control configuration. Representative time histories are included in appendix B, figures B-16–B-19.

As previously noted, the short term response to a wing incidence change at the lower wing angles was a heave response with all flap configurations, and the initial longitudinal response to a forward wing command from the hover position was sluggish with both GF configurations compared to the PF configuration.

The final hover acquisition technique used by some pilots was again somewhat configuration dependent, as discussed earlier. Using the wing incidence technique for final hover acquisition with the GFB configuration, one pilot got into a divergent position PIO (pilot induced oscillation) "that could not be suppressed with any amount of compensation" (the rating was a 7). Time histories showed that the flap was at the lower limit during most of the hover acquisition which caused a distorted wing flap response.

Initially, the tail thruster pitch control power of the GFS configuration was ±0.3 rad/sec^2 which was half the pitch control power of the other two flap configurations (AGARD 577 recommends pitch control power be in the range of 0.4–0.8 rad/sec^2). Three pilots evaluated this configuration without encountering any tail thruster pitch control power limits. However, one pilot, using an aggressive wing tilting technique (see fig. B-19, and compare to fig. B-18), did encounter loss of aircraft control because of tail thruster control power saturation, ". . . an overshoot was developing which required continuous wing beep (wing movement). As power was increased to account for the loss of wing lift, the power-pitch coupling response became apparent and objectionable. It was countered with stick input but when the flaps reached the deflection limit a divergent pitch PIO rapidly developed that resulted in loss of control after 2 oscillations." This resulted in the flying qualities rating of 10. The tail thruster pitch control power of the GFS configuration was increased to ±0.6 rad/sec^2 (the same as the other two configurations), and the problem did not occur again. The same pilot using the same aggressive wing tilting technique evaluated the task again and the rating was a 5.

As before, pilot compensation was required to lead the heave response with throttle and to better predict attaining the hover end position. The workload was primarily in the vertical axis trying to maintain altitude. One pilot noted that, ". . . conditions were ideal and that any complications due to wind, turbulence or visibility would significantly add to the workload." The pilot workload was higher with the GFS configuration than with the GFB configuration. One pilot explained, "(The) workload was a bit higher as a result of (increased) vertical response to wing change, (I) had to predict (i.e., anticipate response) more strongly." Another pilot also perceived a "slight increase in vertical response to wing change" with the GFS configuration, and said it made "the vertical ride a little bumpier."

In general, with the PF configuration the pilots achieved all the desired performance standards. With both GF configurations, the pilots achieved desired performance standards for altitude, heading and buffet, but desired to adequate performance for pitch attitude.

Tail Thruster Pitch Control Power Usage

The maximum pitch control power of the tail thruster was 0.6 rad/sec^2 for both the programmed flap and the geared flap on the beep configurations. As already discussed, the maximum pitch control power of the geared flap on the stick configuration was initially 0.3 rad/sec^2, and was later increased to 0.6 rad/sec^2. Table 6 compares these values to the V/STOL Handling Qualities Criteria (ref. 12) and to previous tilt-wing aircraft (refs. 8 and 12).

Table 6. Pitch control power

	Angular acceleration, rad/sec^2	
	Hover	STOL
Simulated aircraft	0.6	0.6
AGARD 577 criteria	0.4–0.8	0.4–0.6
CL-84-1	1.2	1.2
XC-142	not available	0.45

Two inputs determined the pitch control power used, the pilot's longitudinal stick input and the SAS (stability augmentation system) input, as shown in figure 13. The longitudinal stick input to the tail thruster command logic was the same for each of the three configurations. The SAS input was added to the longitudinal stick input, and the combined pitch control power was limited to 0.6 rad/sec^2.

The tail thruster was not phased out at the higher velocities. The following results on tail thruster pitch control usage during low-speed flight and hover are not affected by this, since all maximum pitch control usage occurred at speeds below 45 knots, except for two cases with the PF which occurred at 57 knots. At these speeds, the elevator alone would still not have been effective enough to provide conventional pitch control.

Figure 20 summarizes the range of pitch control power used by each flap configuration during all the task evaluations (with the exception of a few runs which were not available for examination). For the hover case, the maximum pitch control used with the PF and the GFB configurations is broken down according to pilot longitudinal positioning technique (i.e., wing or stick).

Comparison of the values shown in figure 20 do not show a reduction in pitch control power usage by the geared flap configurations compared to the programmed flap configuration. However, the readers are advised that the figure 20 summary of pitch control usage by each flap configuration represents results at the current stage of development.

Conclusions

1. The pilot ratings showed that in general, the programmed flap and the two geared flap configurations had similar flying qualities. The programmed flap configuration showed levels 1-2 flying qualities during all the tasks except during the hover station keeping with turbulence task which showed level 2 flying qualities. The geared flap configurations generally showed levels 1-2 flying qualities during the descending and decelerating transition to hover and the hover station keeping with turbulence tasks, and level 2 flying qualities during the level inbound transition to hover and the longitudinal reposition tasks.

2. Although many of the aircraft characteristics were similar among the three flap configurations, two main differences were the longitudinal aircraft response in hover and the amount of time spent in buffet. With the geared flap configurations, the initial longitudinal aircraft response to a forward wing command from hover was a rearward acceleration transient. This acceleration transient resulted in sluggish longitudinal aircraft response and hence in degraded speed predictability near hover with the geared flap configurations compared to the programmed flap configuration. By adding damping about the wing pivot, this simulation reduced the magnitude of the transient response to about a third of the magnitudes seen in the first simulation. The amount of time spent in buffet was greater with both geared flap configurations than with the programmed flap configuration because of lower flap deflections for similar wing incidences.

3. The pitch attitude stability augmentation system (SAS) added to the flap configurations during the second simulation was a significant improvement over the pitch rate SAS of the first simulation, and greatly alleviated the pilot workload associated with pitch axis control.

4. At the current level of development the results did not show a reduction in tail thruster pitch control power usage for the geared flap configurations compared to the programmed flap configuration.

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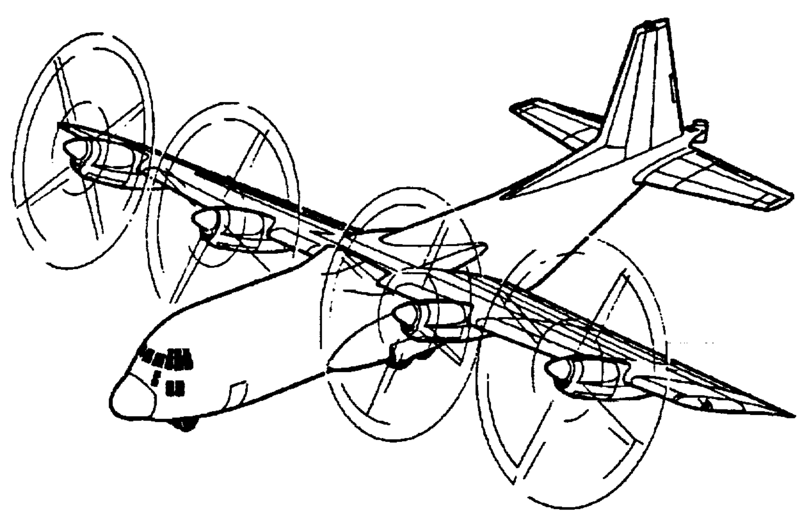


Figure 1. Simulated tilt-wing aircraft.

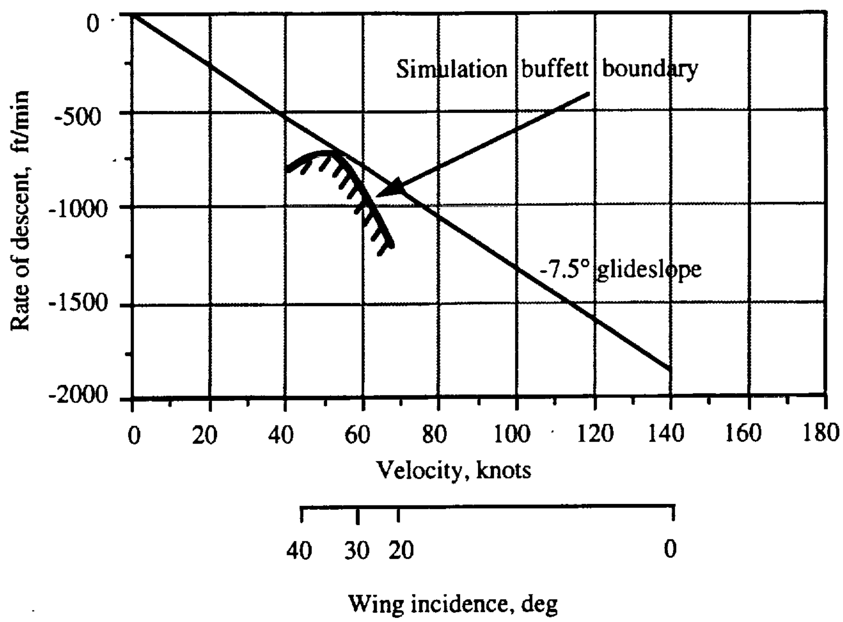


Figure 2. Simulation buffet boundary for –7.5° glideslope.

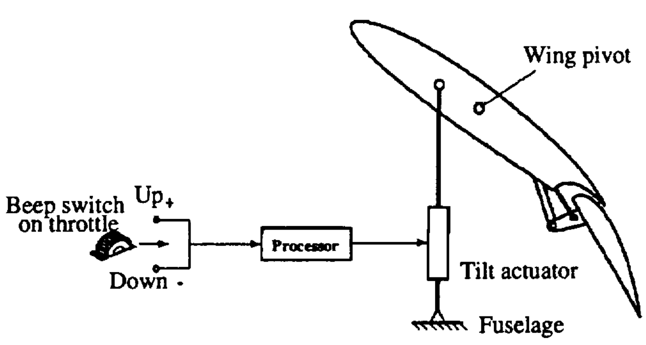


Figure 3. Programmed flap control concept.

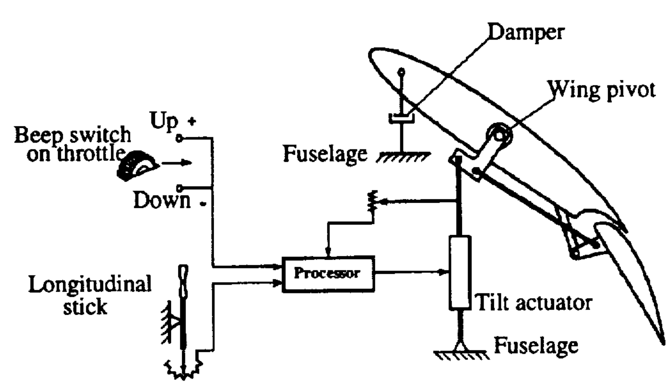


Figure 4. Geared flap control concept.

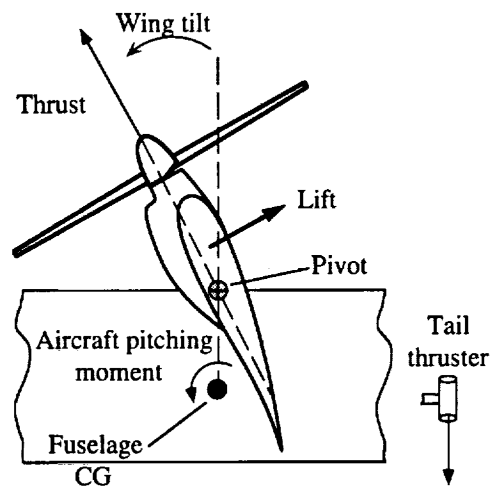


Figure 5. Programmed flap pitching moment due to wing rotation.

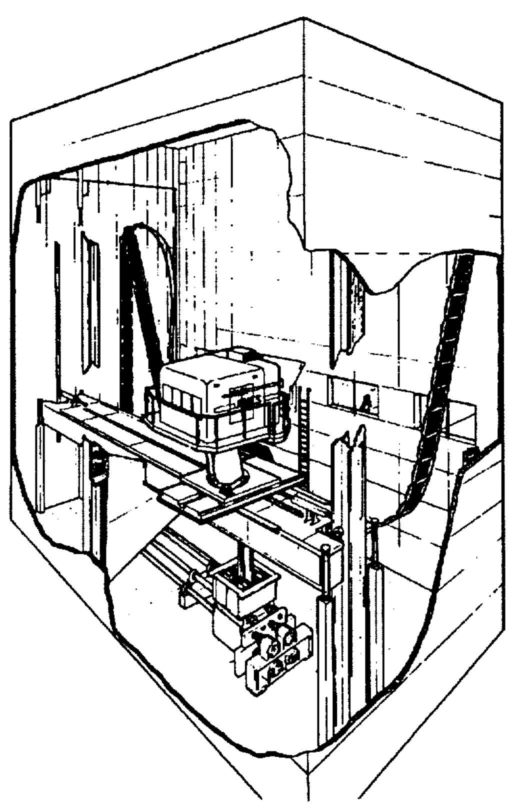


Figure 6. Vertical Motion Simulator.

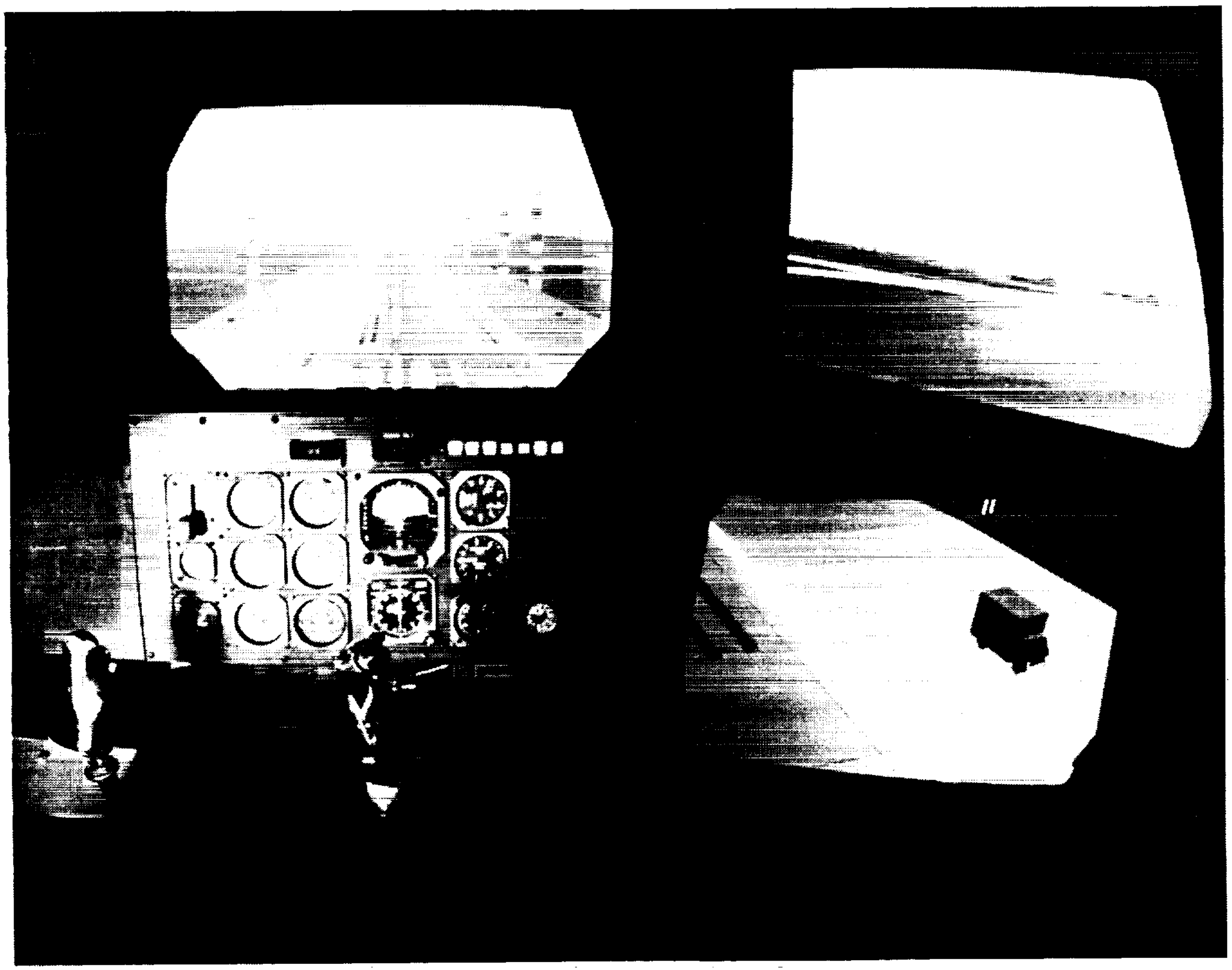


Figure 7. Simulator cockpit arrangement.

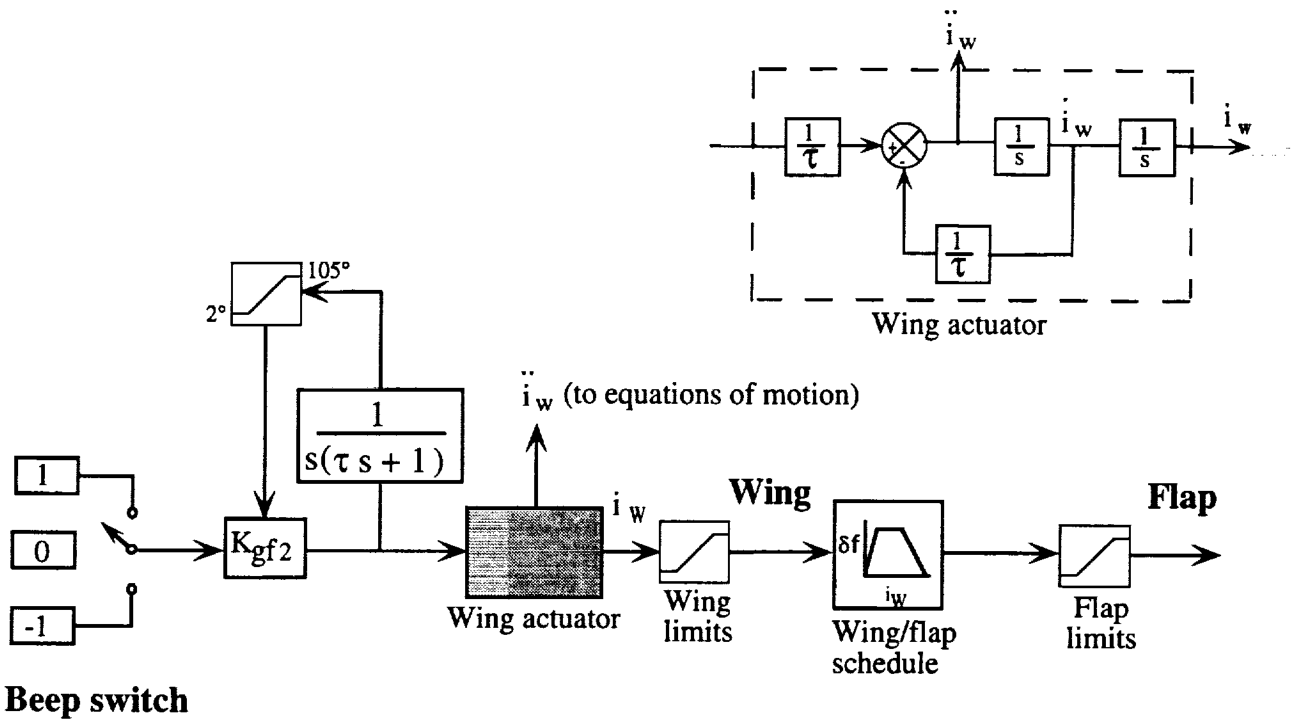


Figure 8. Programmed flap control.

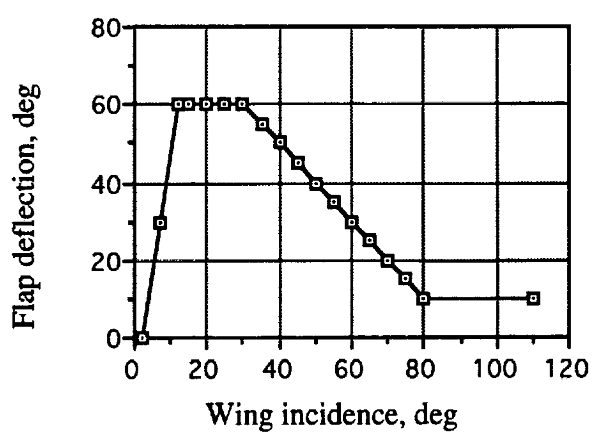


Figure 9. Wing/flap schedule for programmed flap.

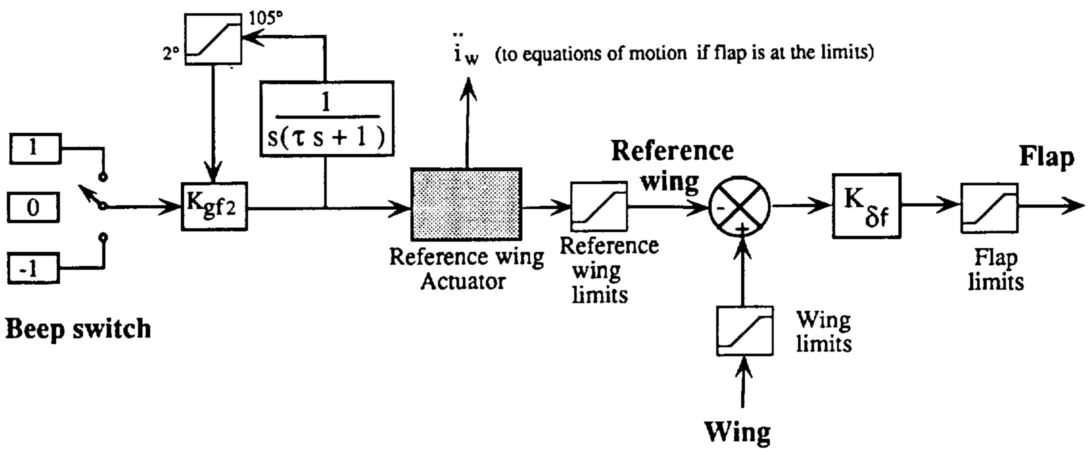


Figure 10. Geared flap on the beep control.

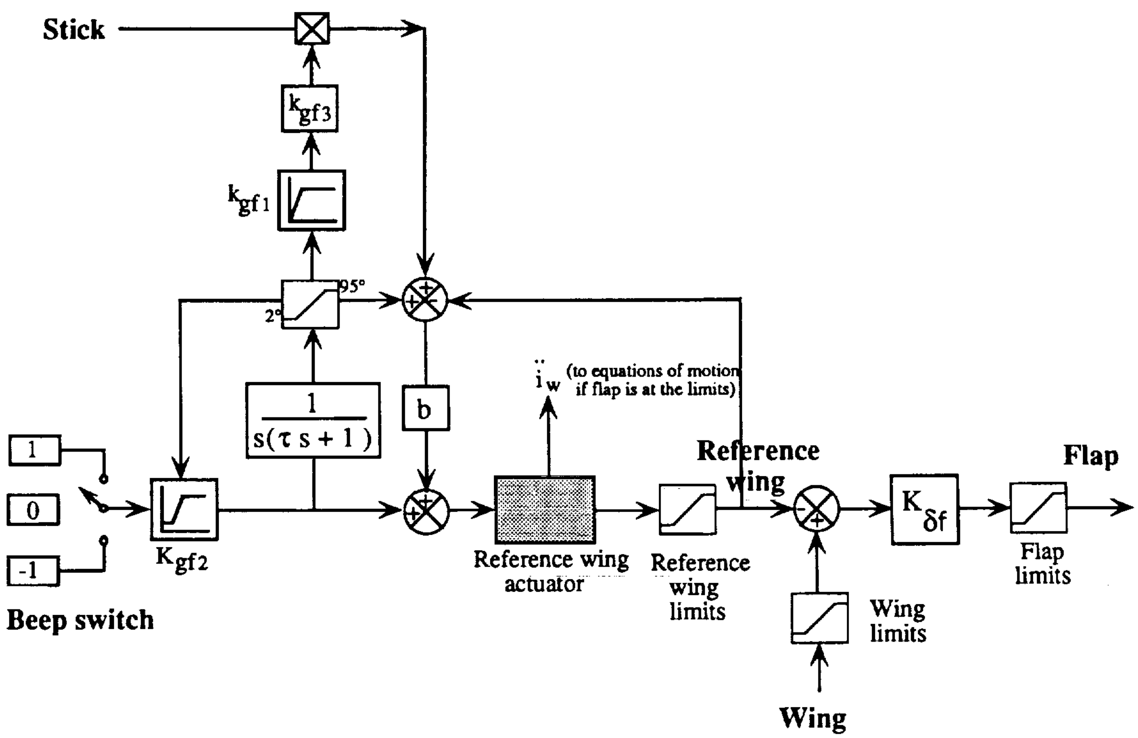
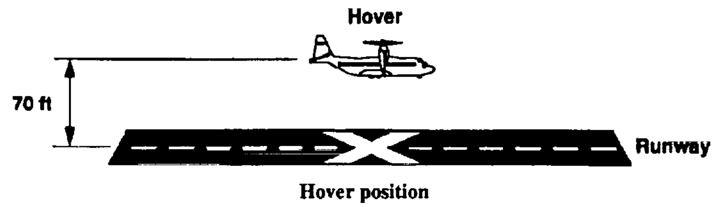
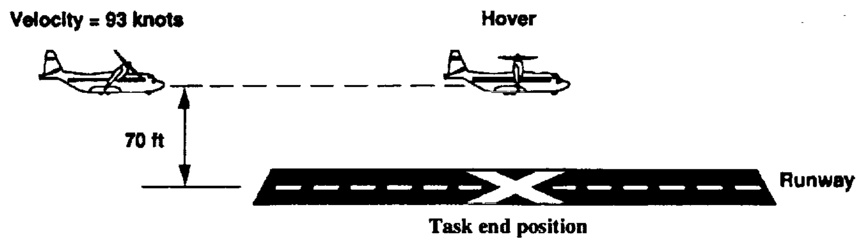


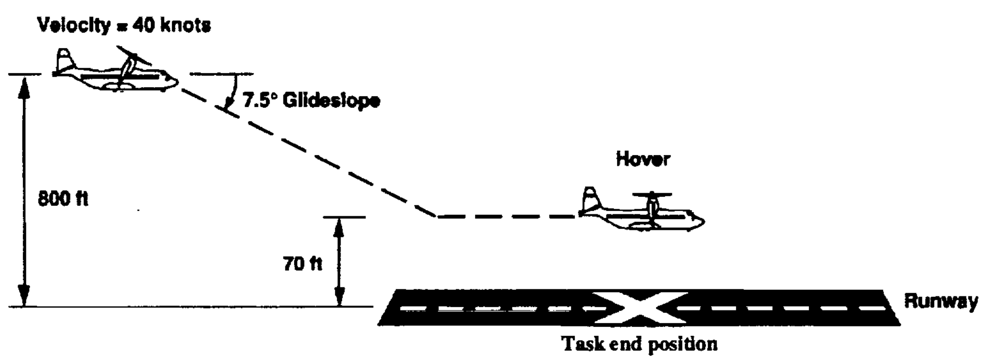
Figure 11. Geared flap on the stick control.



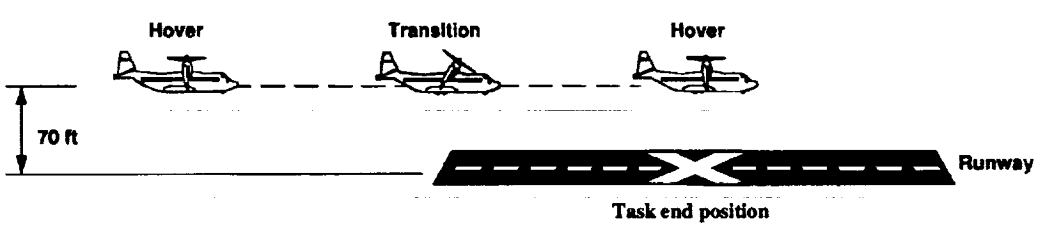
Hover station keeping with turbulence



Level inbound transition to hover



Descending decelerating inbound transition to hover



Longitudinal reposition

Figure 12. Evaluation tasks.

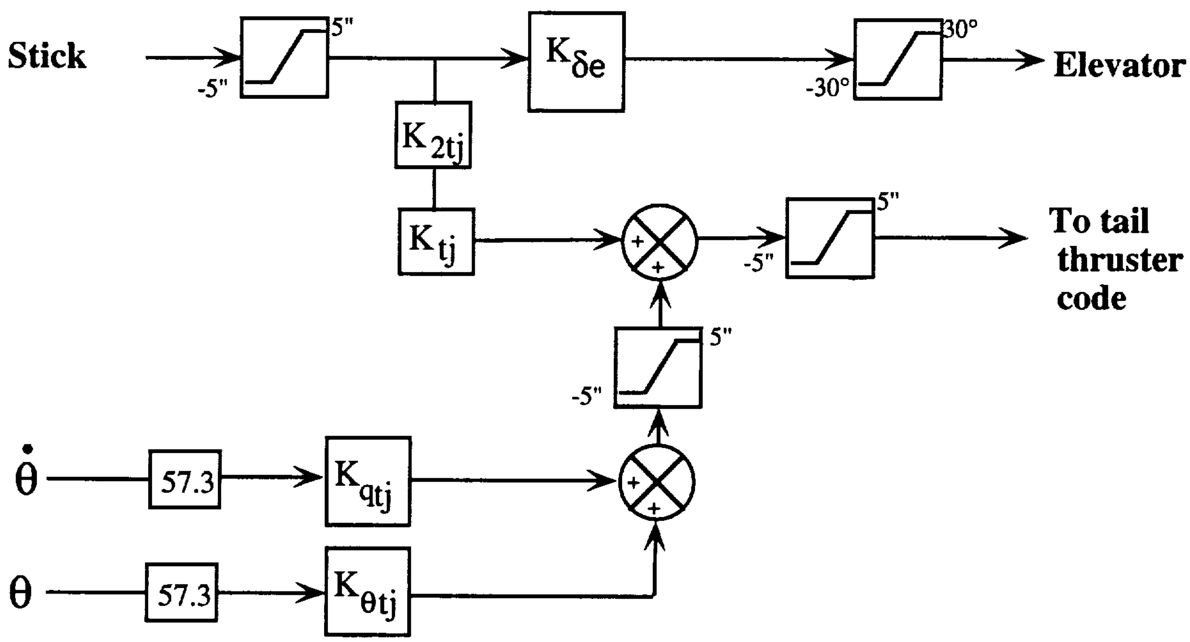


Figure 13. Pitch axis stabilization.

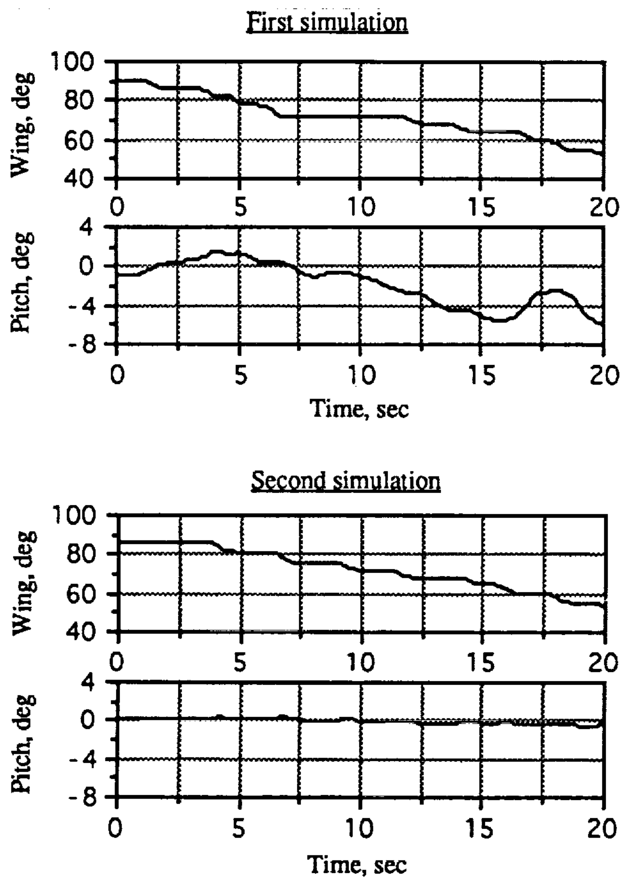
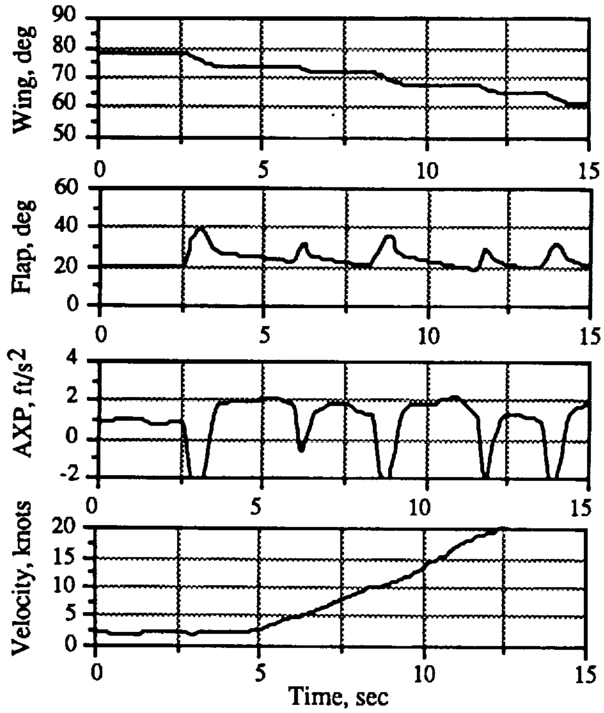
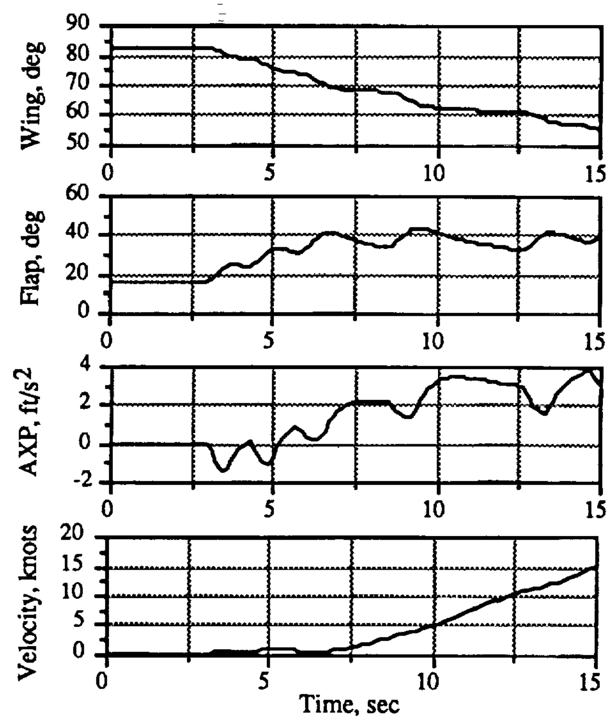


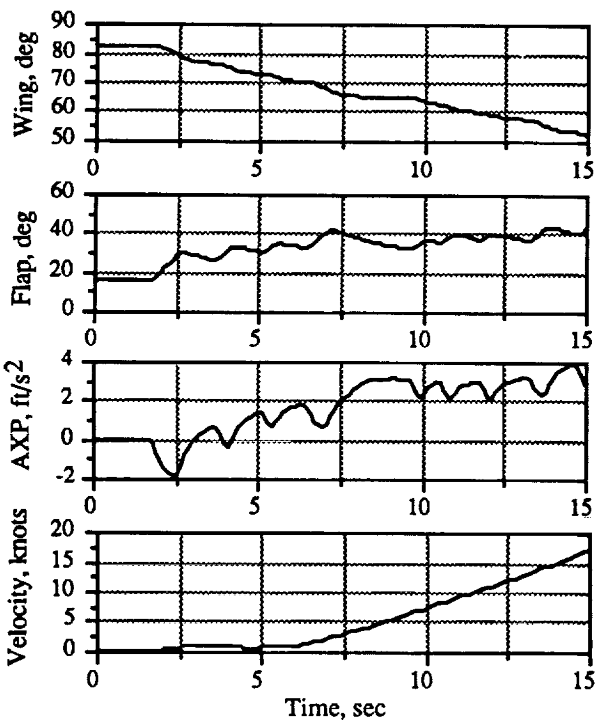
Figure 14. Time histories before and after pitch attitude stabilization,during a typical transition from hover.



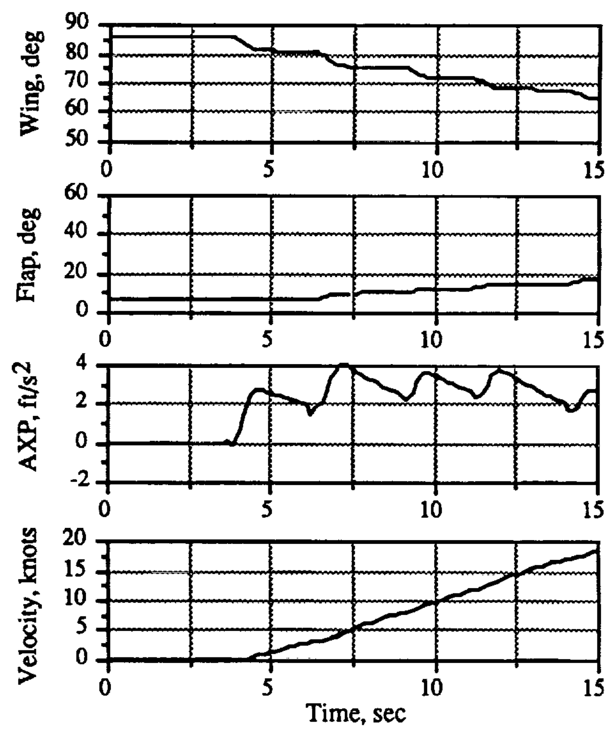
(a) Geared flap on the beep (without damping)



(b) Geared flap on the beep (damping added)



(c) Geared flap on the stick (damping added)



(d) Programmed flap

Figure 15. Time histories during transitions from hover using beep inputs.

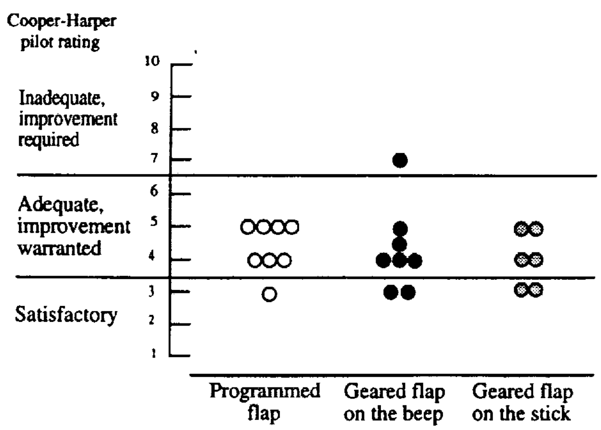


Figure 16. Pilot evaluations of hover with turbulence.

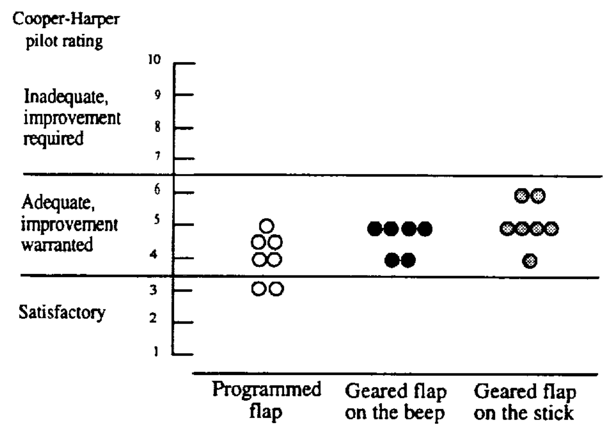


Figure 17. Pilot evaluations of level inbound transition to hover.

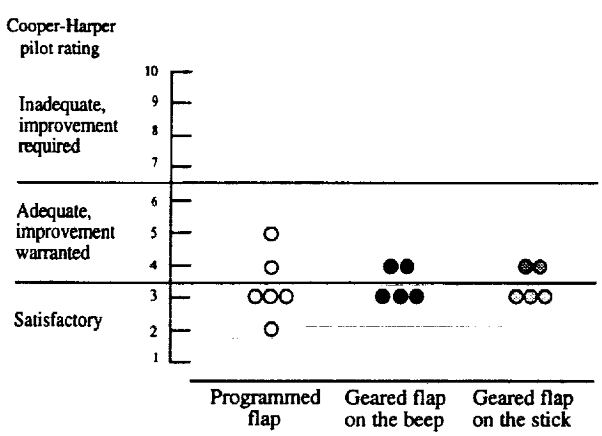


Figure 18. Pilot evaluations of descending decelerating inbound transition to hover.

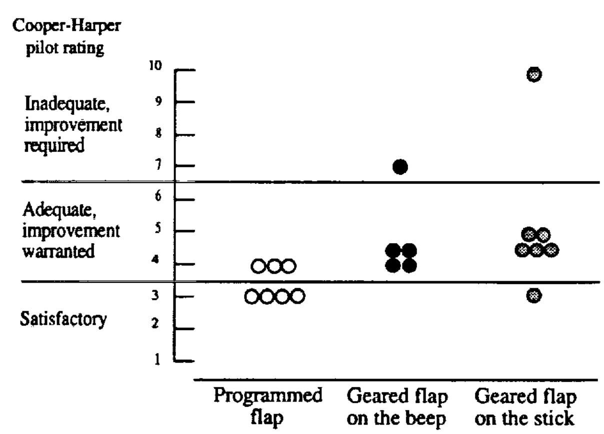


Figure 19. Pilot evaluations of longitudinal reposition.

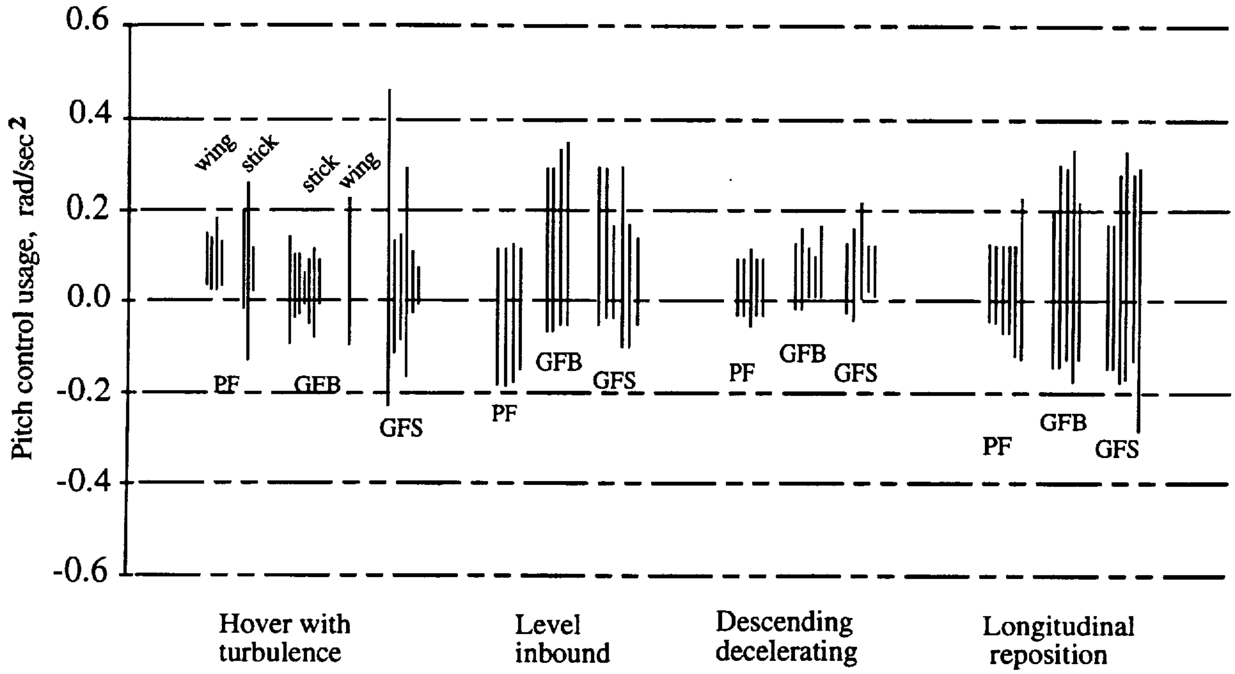


Figure 20. Range of pitch control usage during evaluation tasks.

Appendix A

Control gains and limits are listed in table A-1, and control system table look-ups are shown in figures A-1–A-3.

Table A-1. Control gains and limits

Programmed flap	
τ	0.25 sec
Wing limits	2°–105°
Flap limits	0°–60°
K_{gf2}	Look-up (see fig. A-1)
Geared flap on the beep	
τ	0.25 sec
Wing limits	2°–105°
Reference wing limits	1°–105°
Flap limits	0°–60°
$K_{\delta f}$	8
K_{gf2}	Look-up (see fig. A-1)
Geared flap on the stick	
τ	0.25 sec
Wing limits	2°–105°
Reference wing limits	1°–100°
Flap limits	0°–60°
b	5 1/sec
$K_{\delta f}$	8
K_{gf1}	Look-up (see fig. A-2)
K_{gf2}	Look-up (see fig. A-1)
K_{gf3}	2
Pitch axis stabilization	
$K_{\delta e}$	6 deg/in.
K_{tj}	Look-up (see fig. A-3)
K_{2tj}	2
Kq_{tj}	0.7 in./deg
$k\theta_{tj}$	1.0 in./deg

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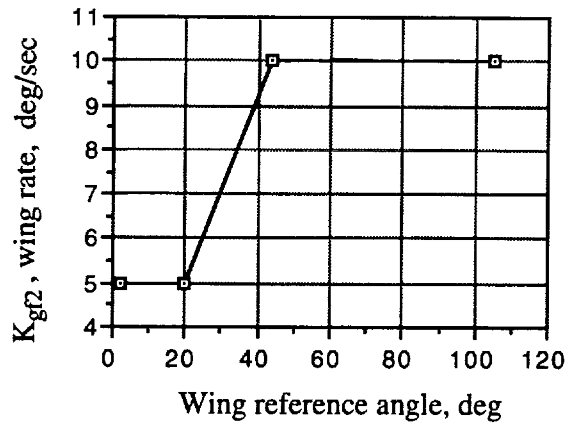

Figure A-1. K_{gf2} table look-up.

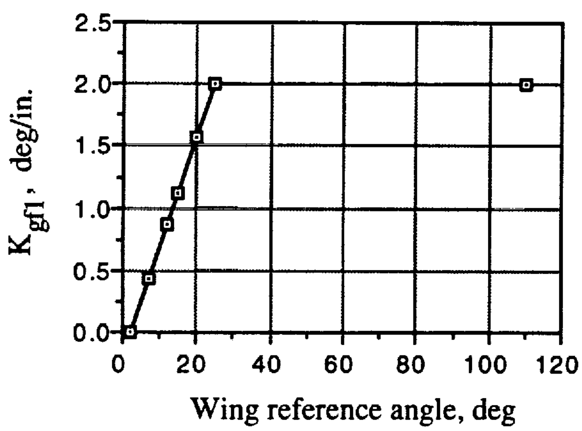

Figure A-2. K_{gf1} table look-up.

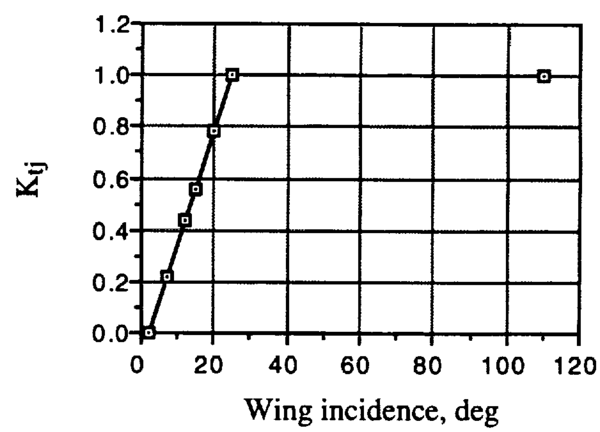

Figure A-3. K_{tj} table look-up.

Appendix B

Representative time histories for the three flap configurations and all the evaluation tasks are included in this section. The run number is identified in parenthesis, so the reader can correlate with the pilot comments in appendix C. The pitch attitude SAS was turned on during all the evaluation runs.

Task 1: Hover Station Keeping in Turbulence

Figure B-1. Programmed flap using wing technique (run 130).

Figure B-2. Programmed flap using stick technique (run 124).

Figure B-3. Geared flap on the beep using stick technique (run 127).

Figure B-4. Geared flap on the beep using wing technique (run 128).

Figure B-5. Geared flap on the stick (run 123).

In addition, the following runs are included to compare pitch activity (discussed in this report). These were flown by the same pilot using the stick technique (pitch adjustments) in all the runs. As with the time histories above, the turbulence level was the same in all the runs, 8 ft/sec rms.

Figure B-6. Geared flap on the stick (run 53).

Figure B-7. Programmed flap (run 52).

Figure B-8. Geared flap on the beep (run 51).

Task 2: Level Inbound Transition to Hover

Figure B-9. Programmed flap (run 36).

Figure B-10. Geared flap on the beep (run 37).

Figure B-11. Geared flap on the stick (run 38).

Task 3: Descending Decelerating Inbound Transition to Hover

Figure B-12. Time histories scales for this task (no room on the time histories).

Figure B-13. Programmed flap (run 115).

Figure B-14. Geared flap on the beep (run 116).

Figure B-15. Geared flap on the stick (run 121).

Task 4: Longitudinal Reposition

Figure B-16. Programmed flap (run 82).

Figure B-17. Geared flap on the beep (run 84).

Figure B-18. Geared flap on the stick (run 83).

Figure B-19. Geared flap on the stick (run 93, for comparison with run 83; discussed in this report).

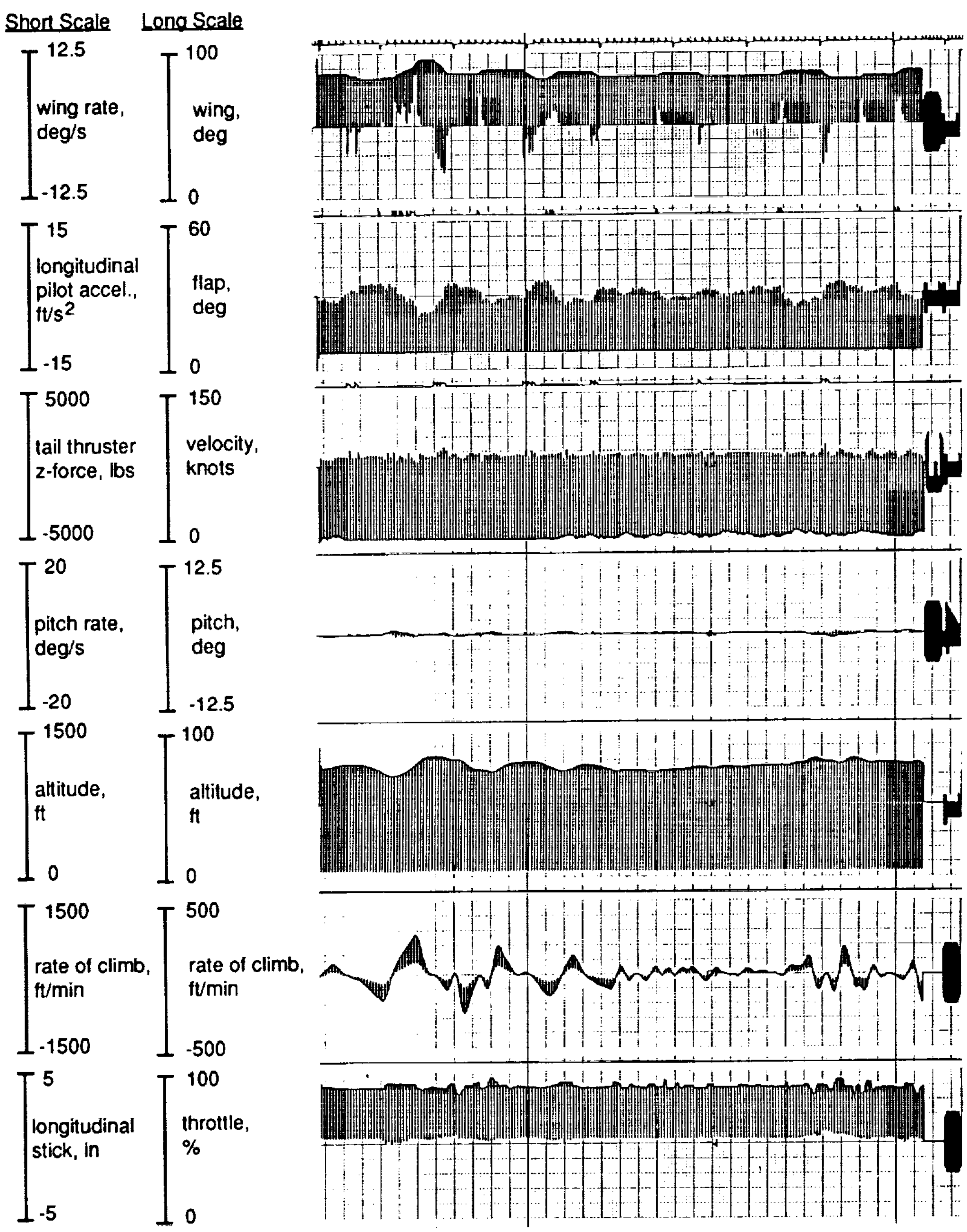

Figure B-1. Programmed flap using wing technique (run 130).

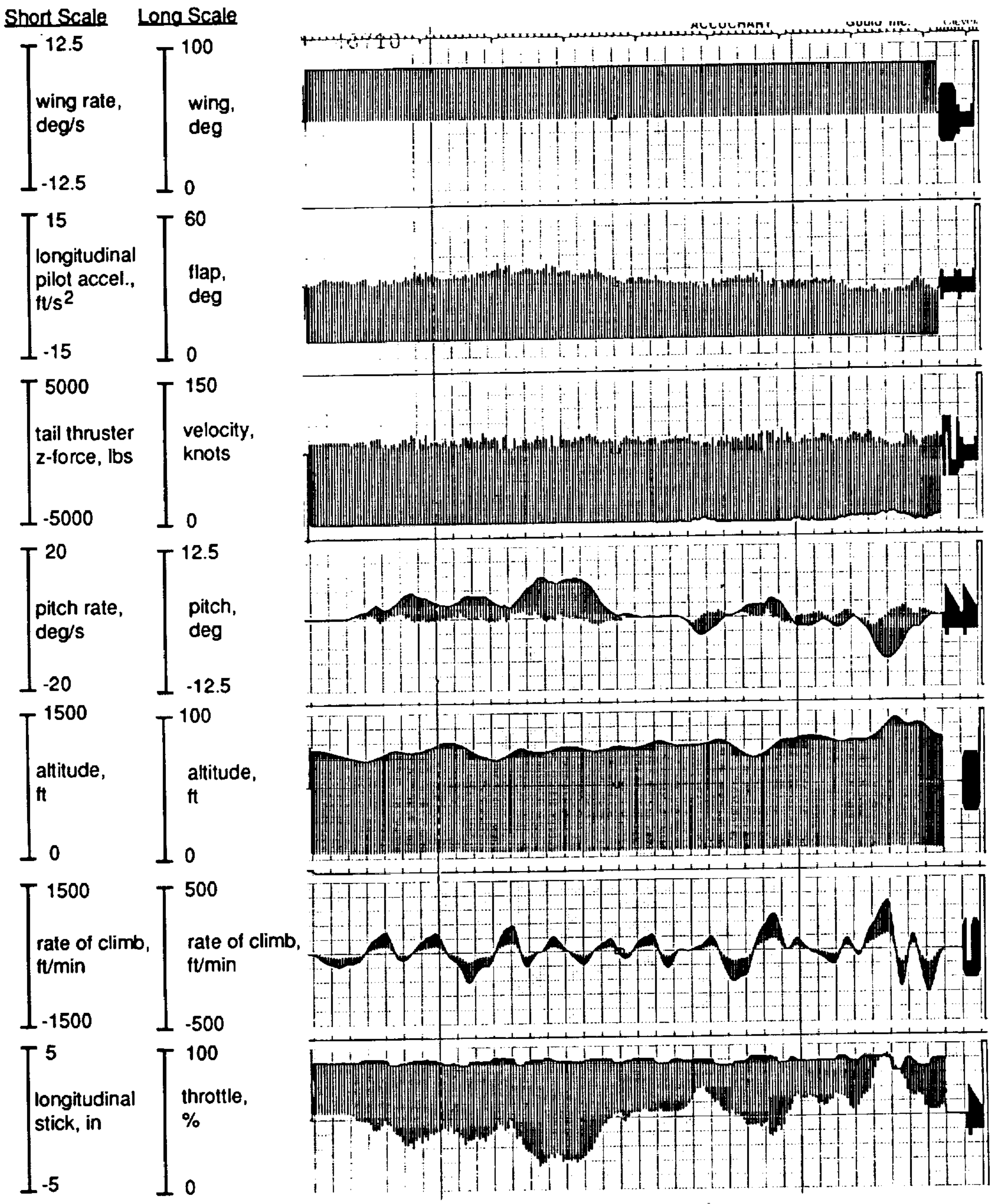

Figure B-2. Programmed flap using stick technique (run 124).

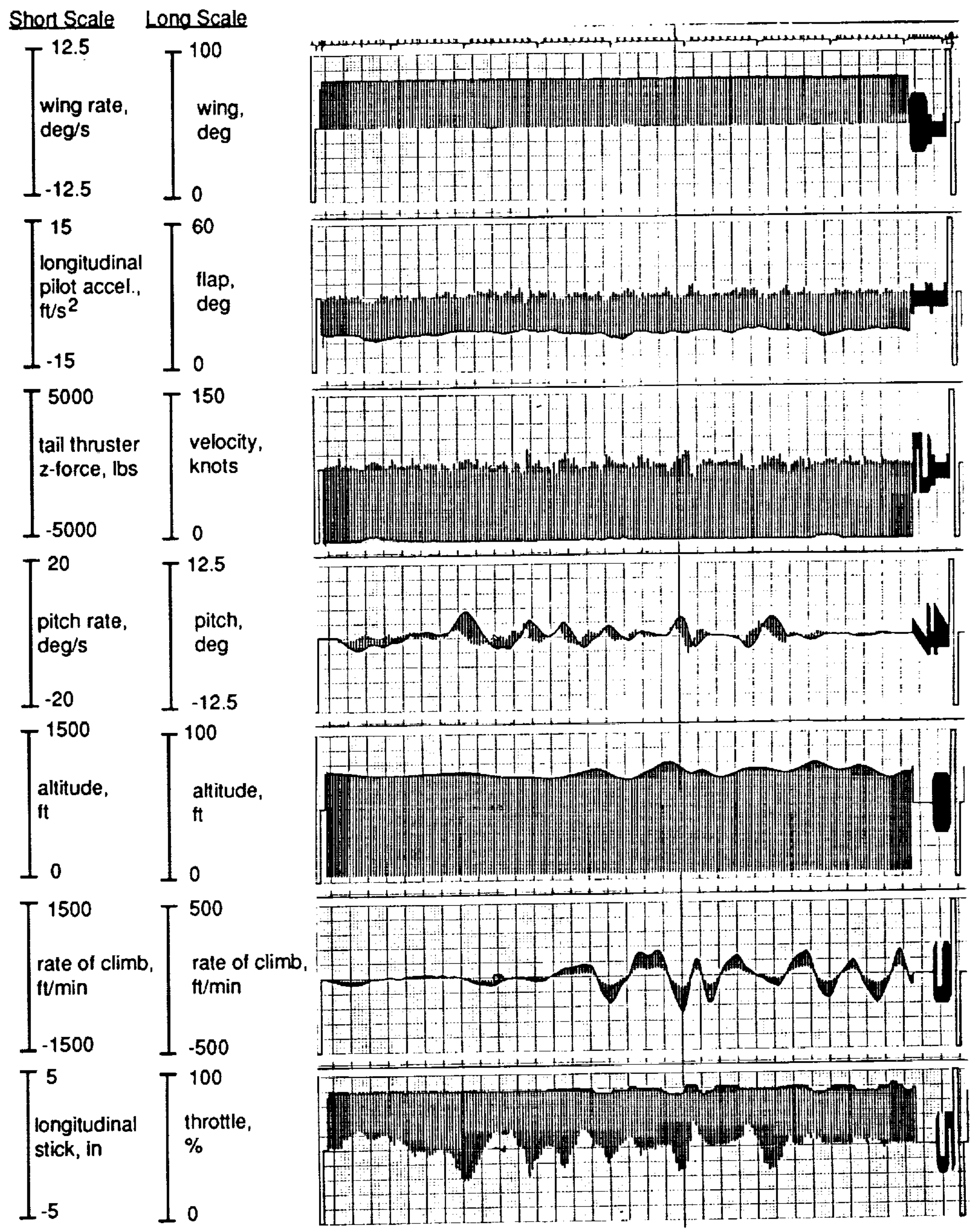

Figure B-3. Geared flap on the beep using stick technique (run 127).

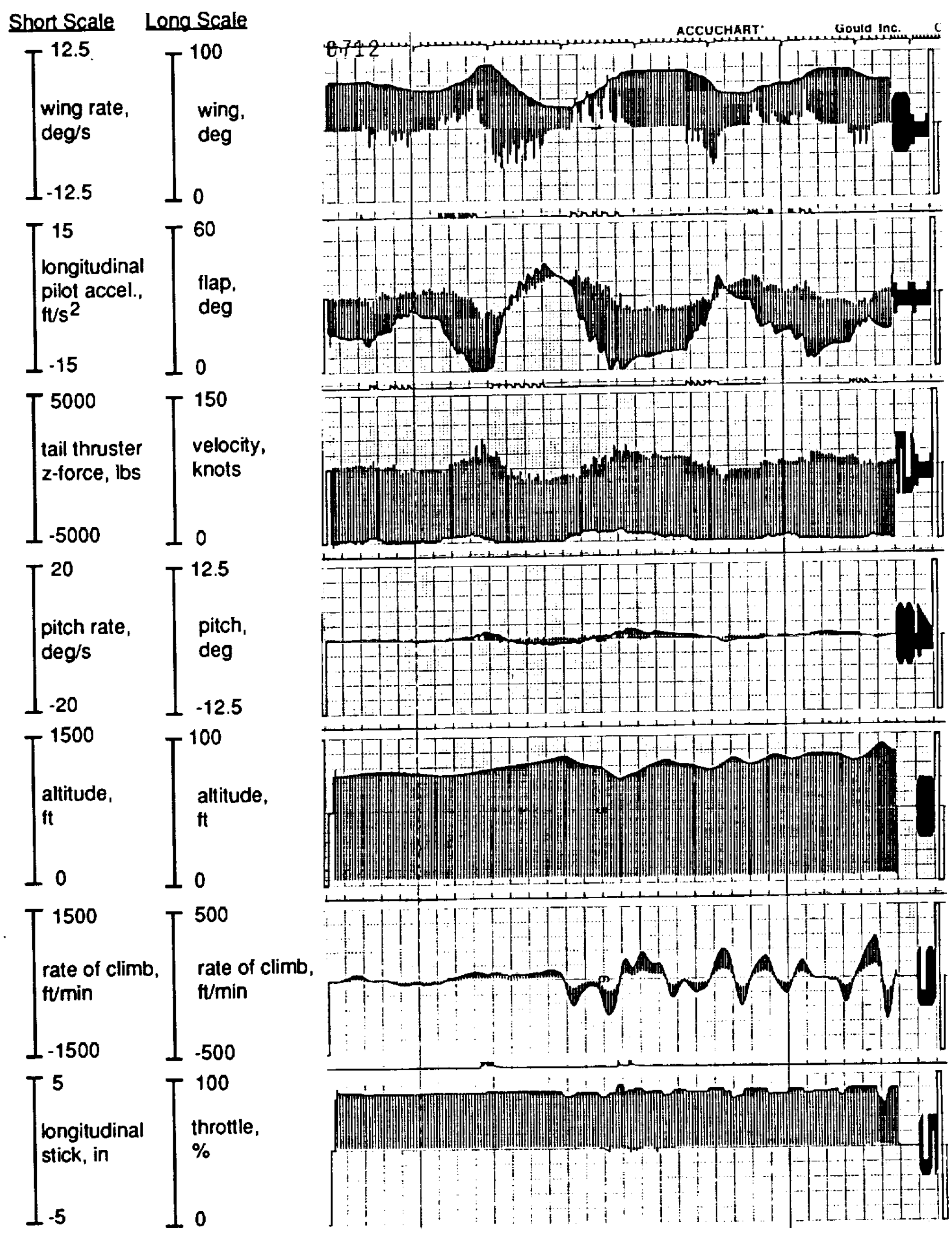

Figure B-4. Geared flap on the beep using wing technique (run 128).

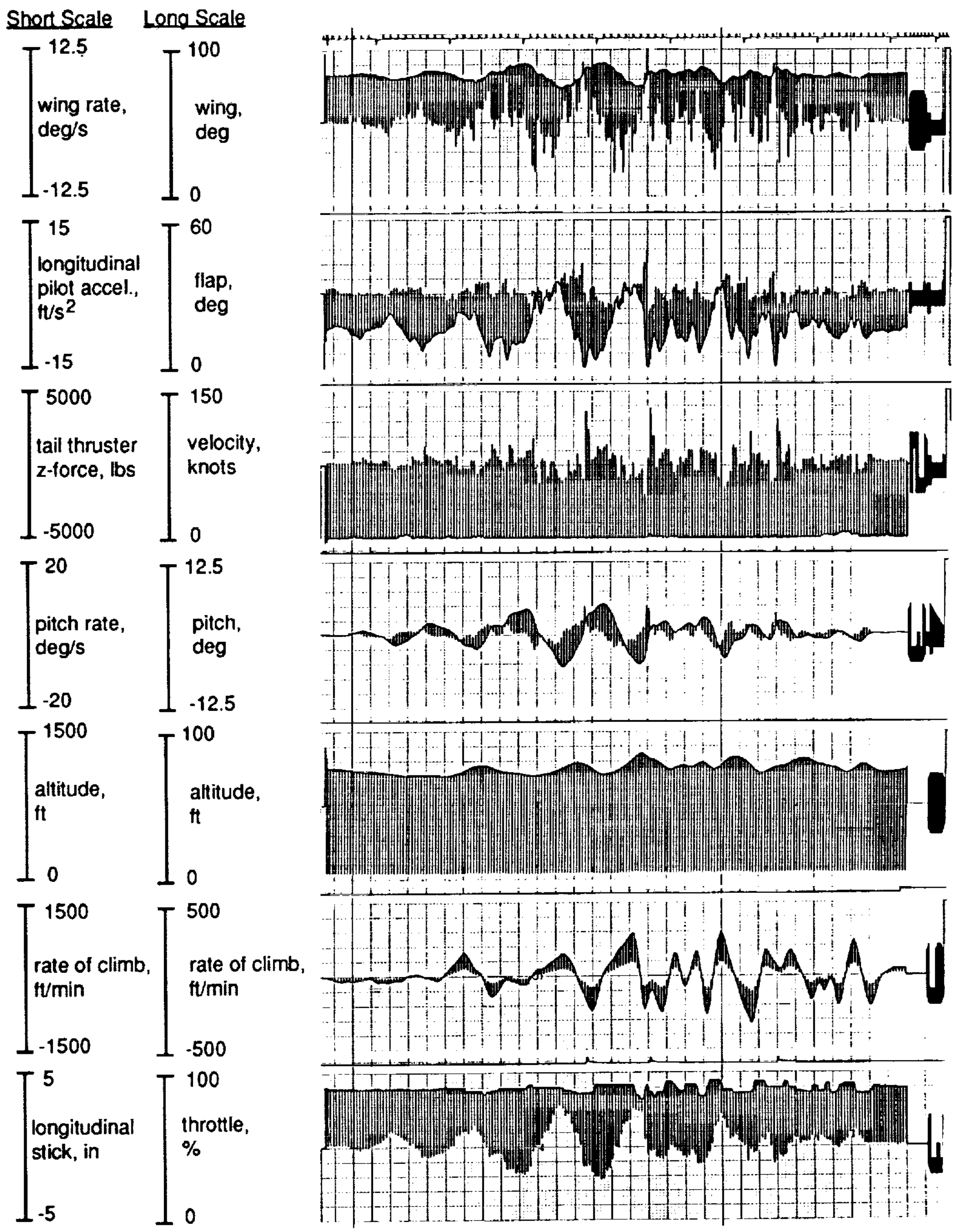

Figure B-5. Geared flap on the stick (run 123).

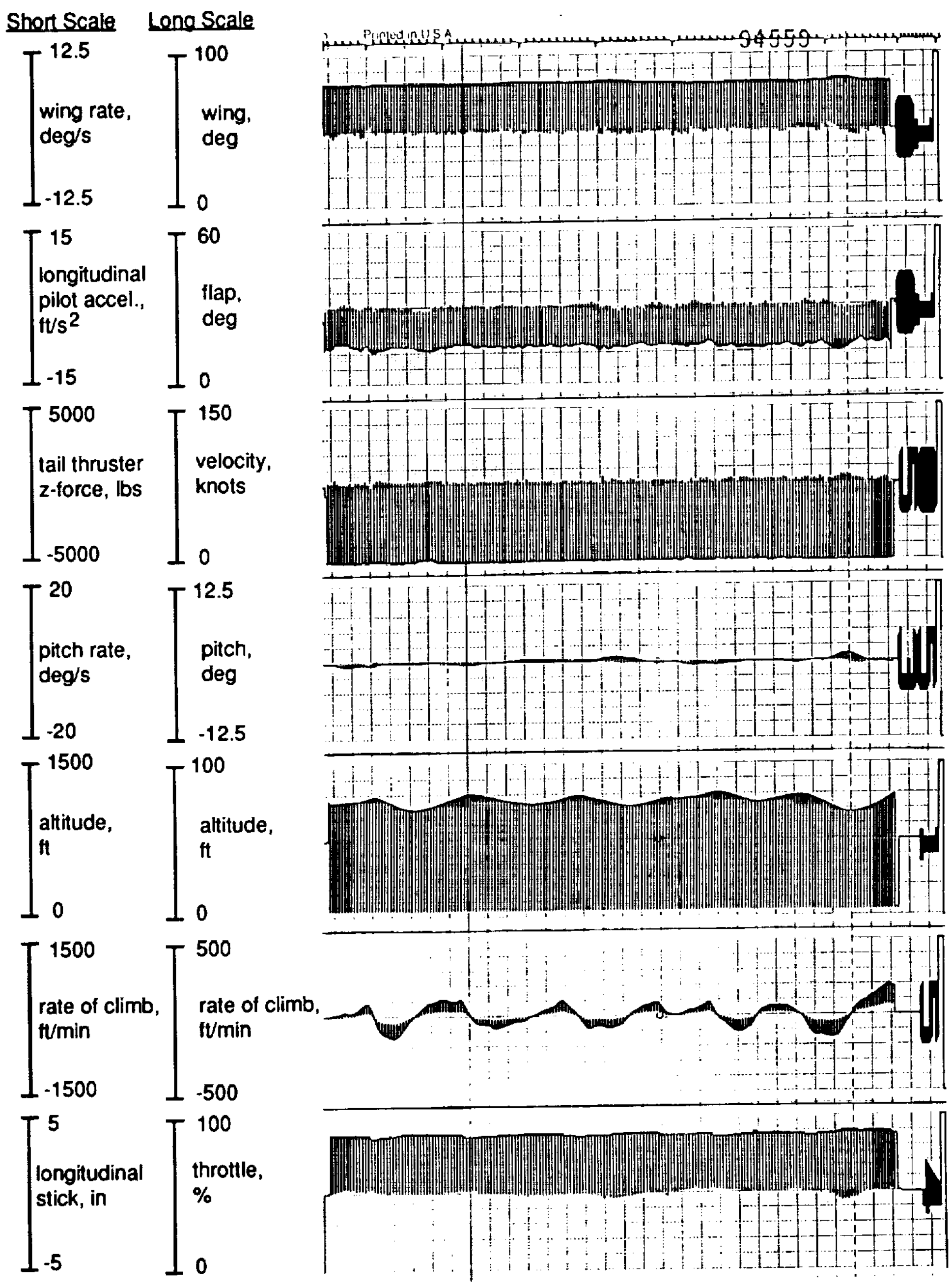

Figure B-6. Geared flap on the stick (run 53).

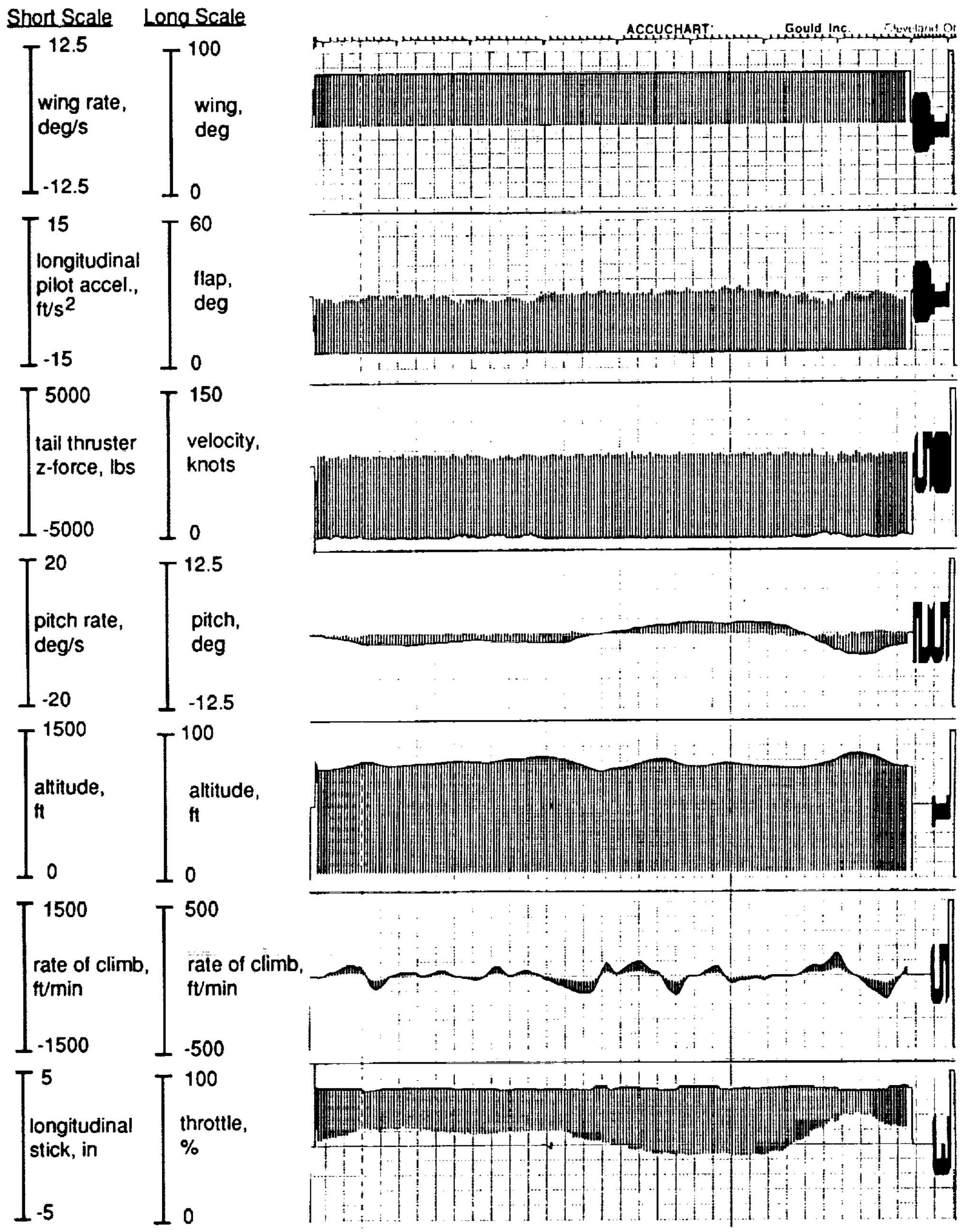

Figure B-7. Programmed flap (run 52).

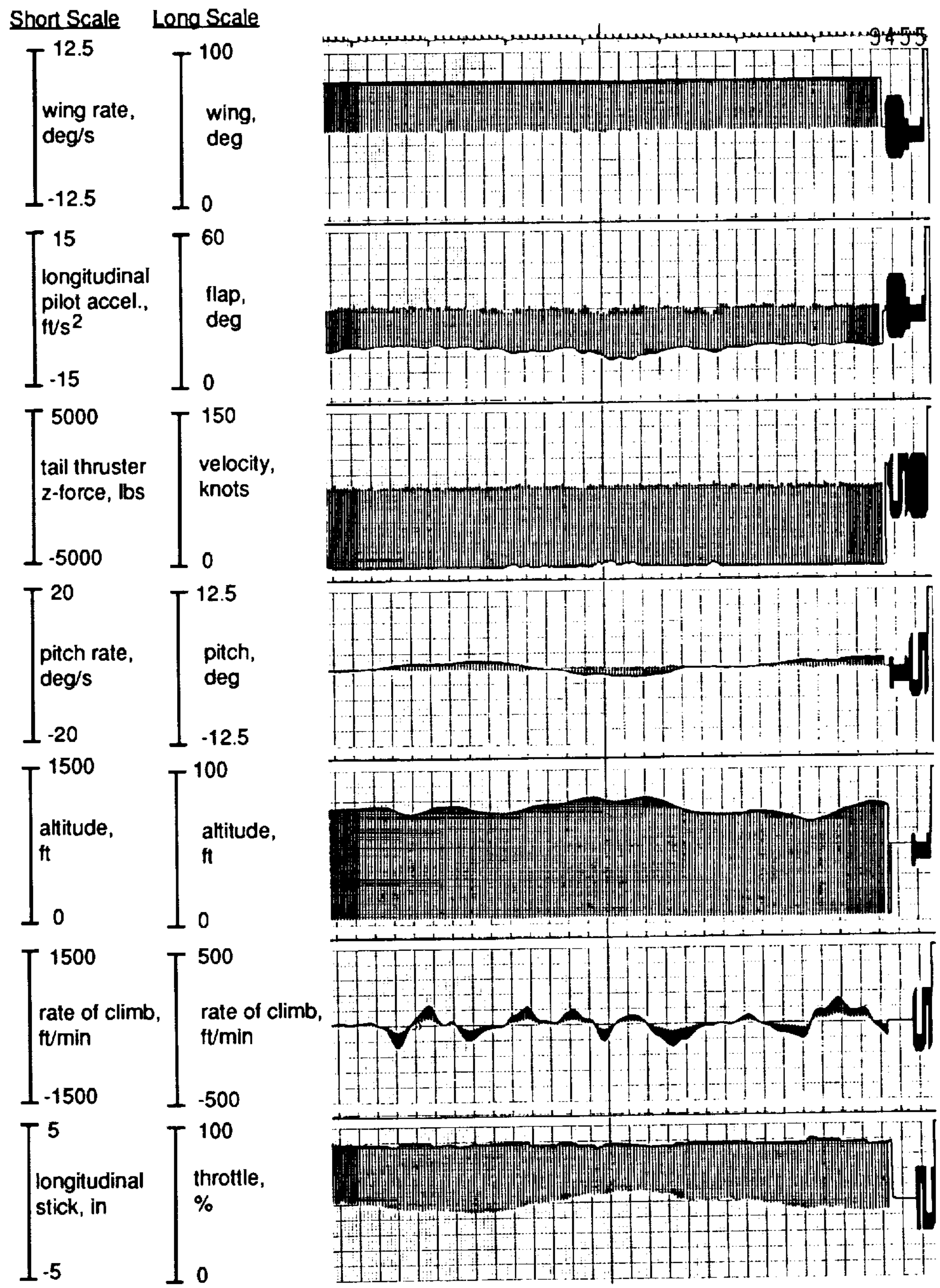

Figure B-8 . Geared flap on the beep (run 51).

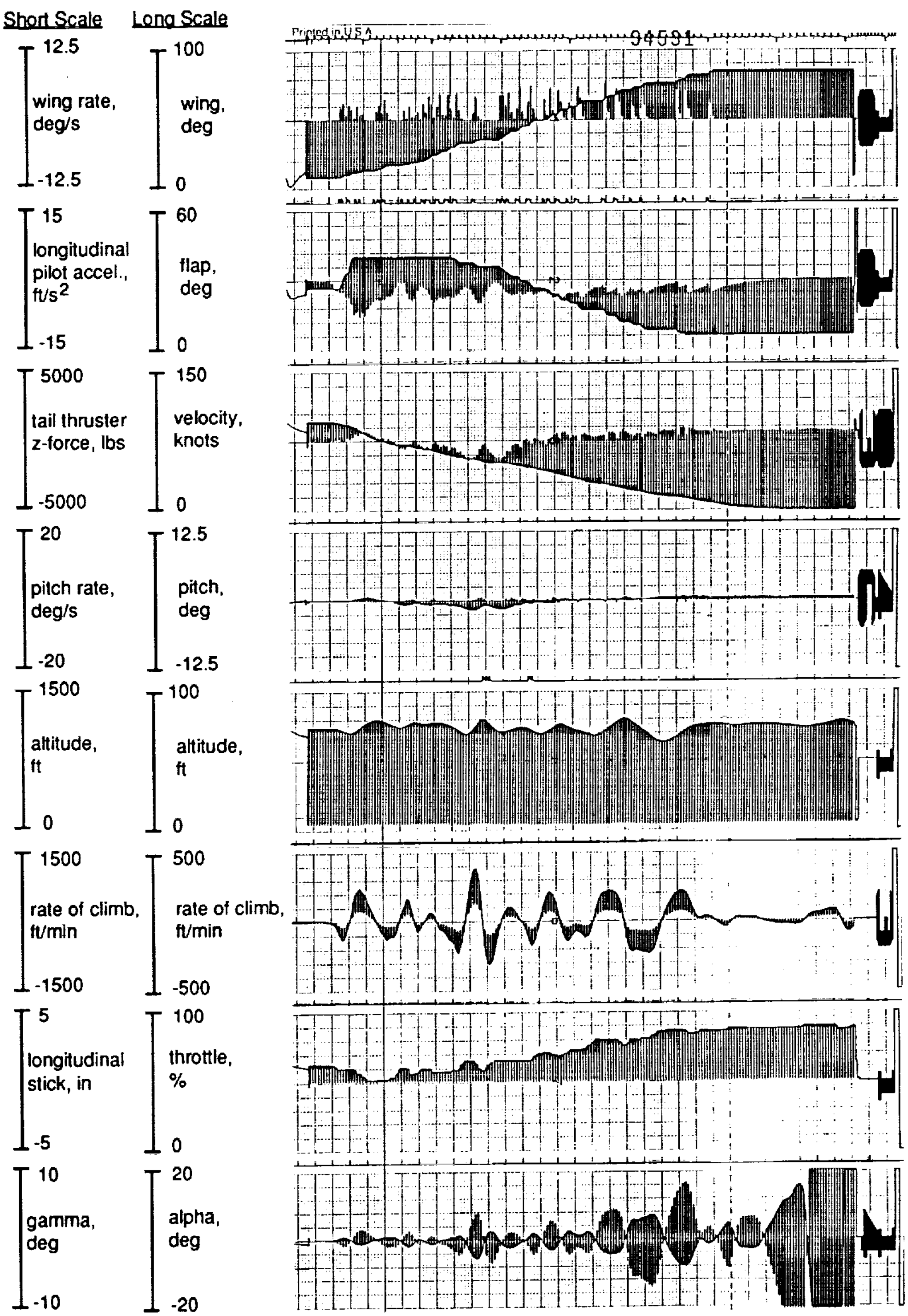

Figure B-9. Programmed flap (run 36).

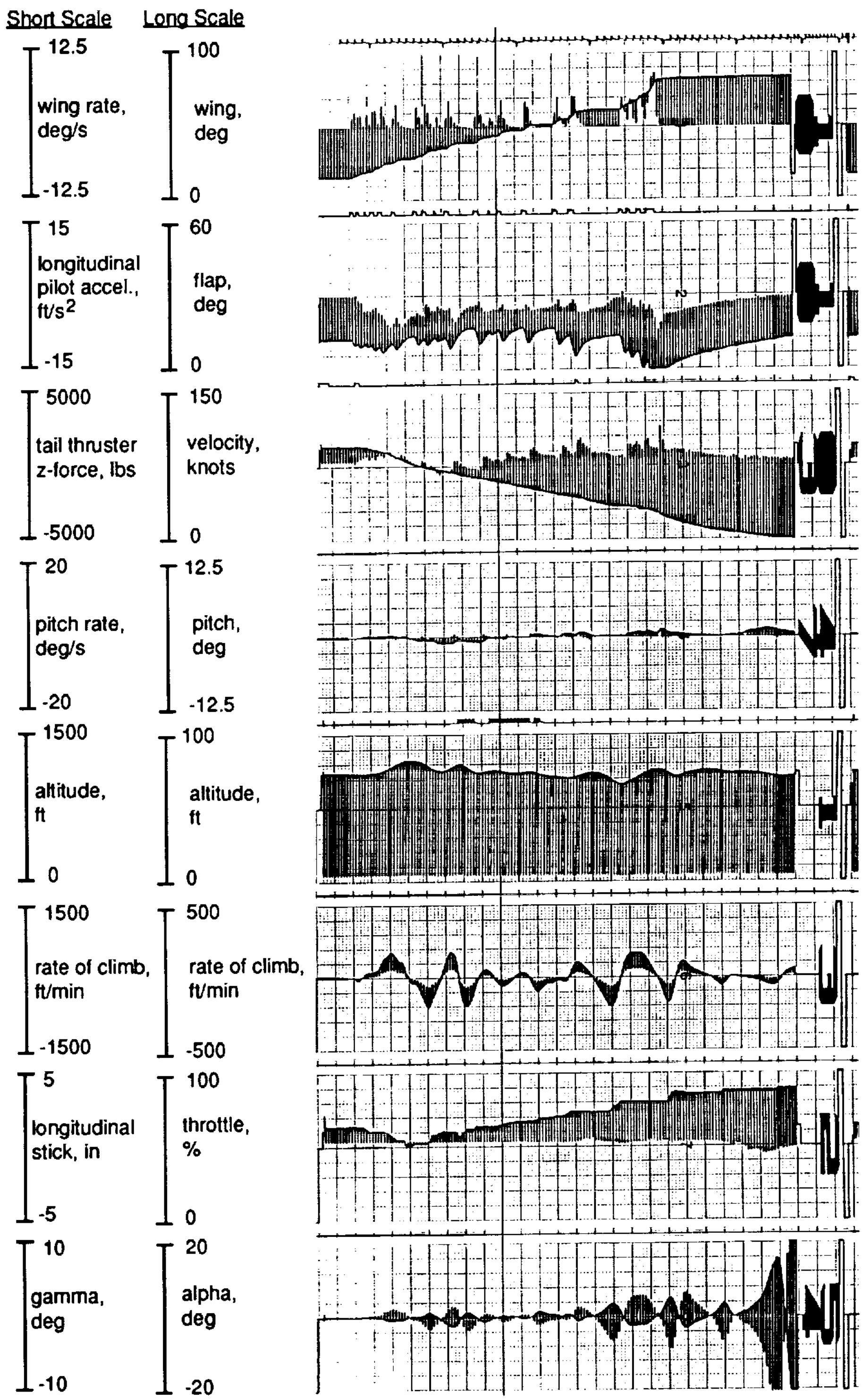

Figure B-10. Geared flap on the beep (run 37).

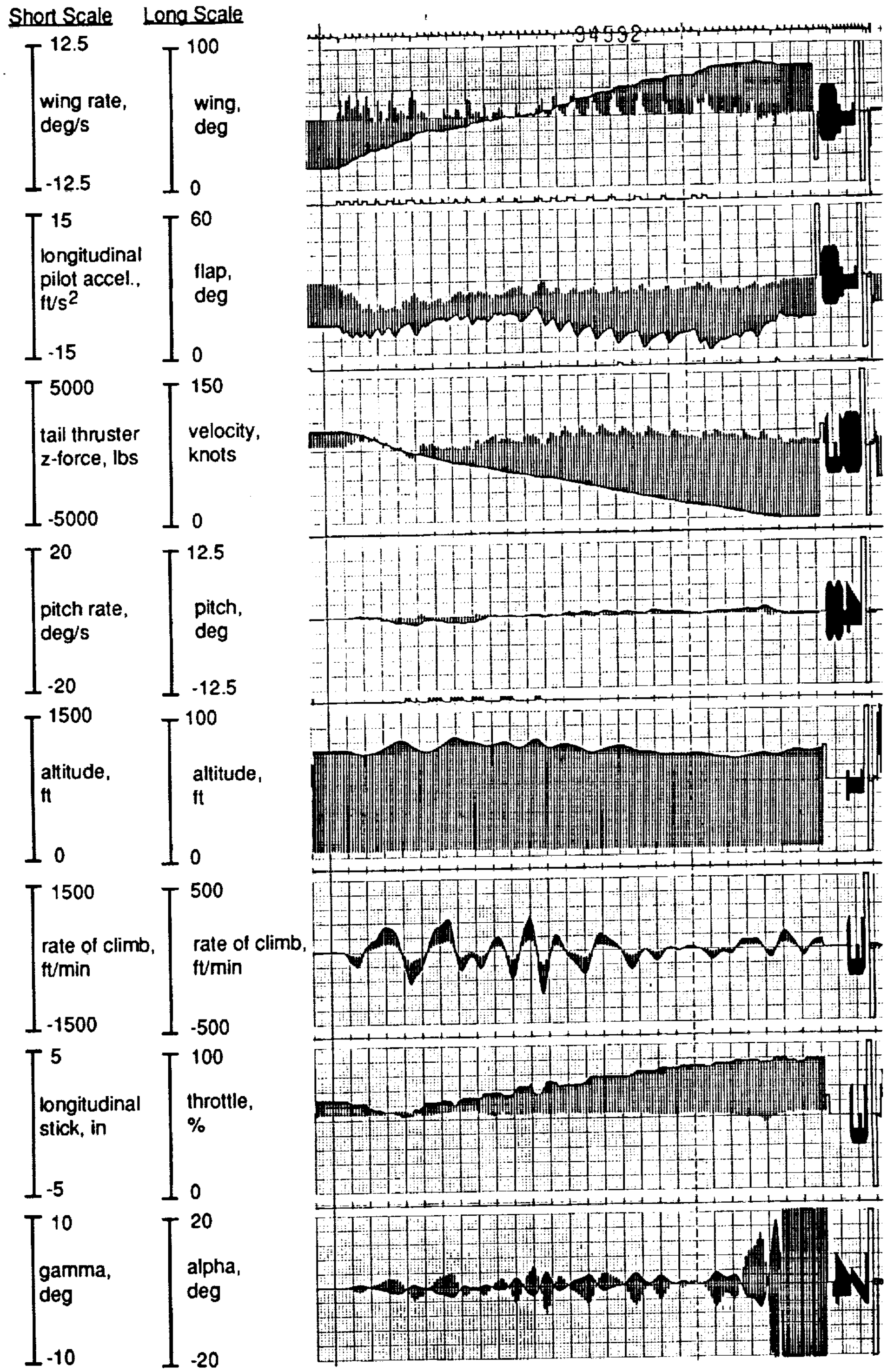

Figure B-11. Geared flap on the stick (run 38).

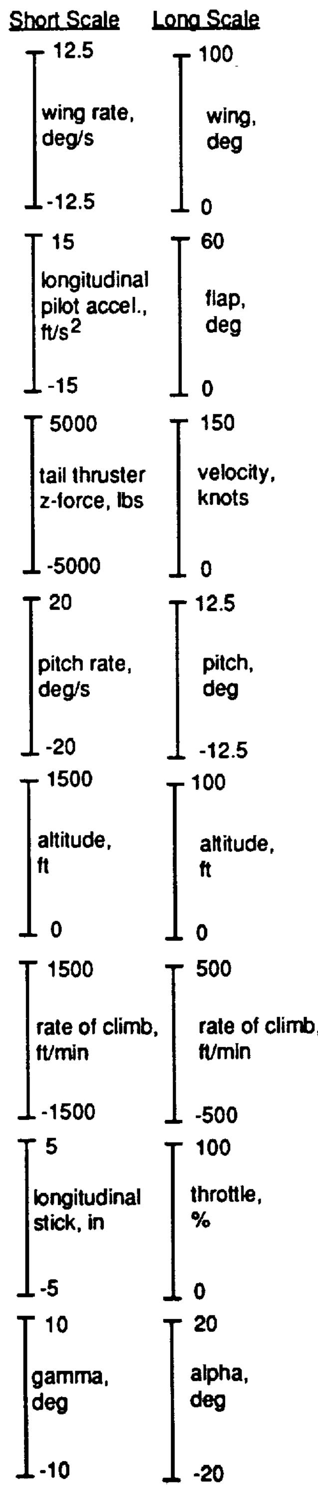

Figure B-12. Time histories scales for descending decelerating inbound transition to hover task.

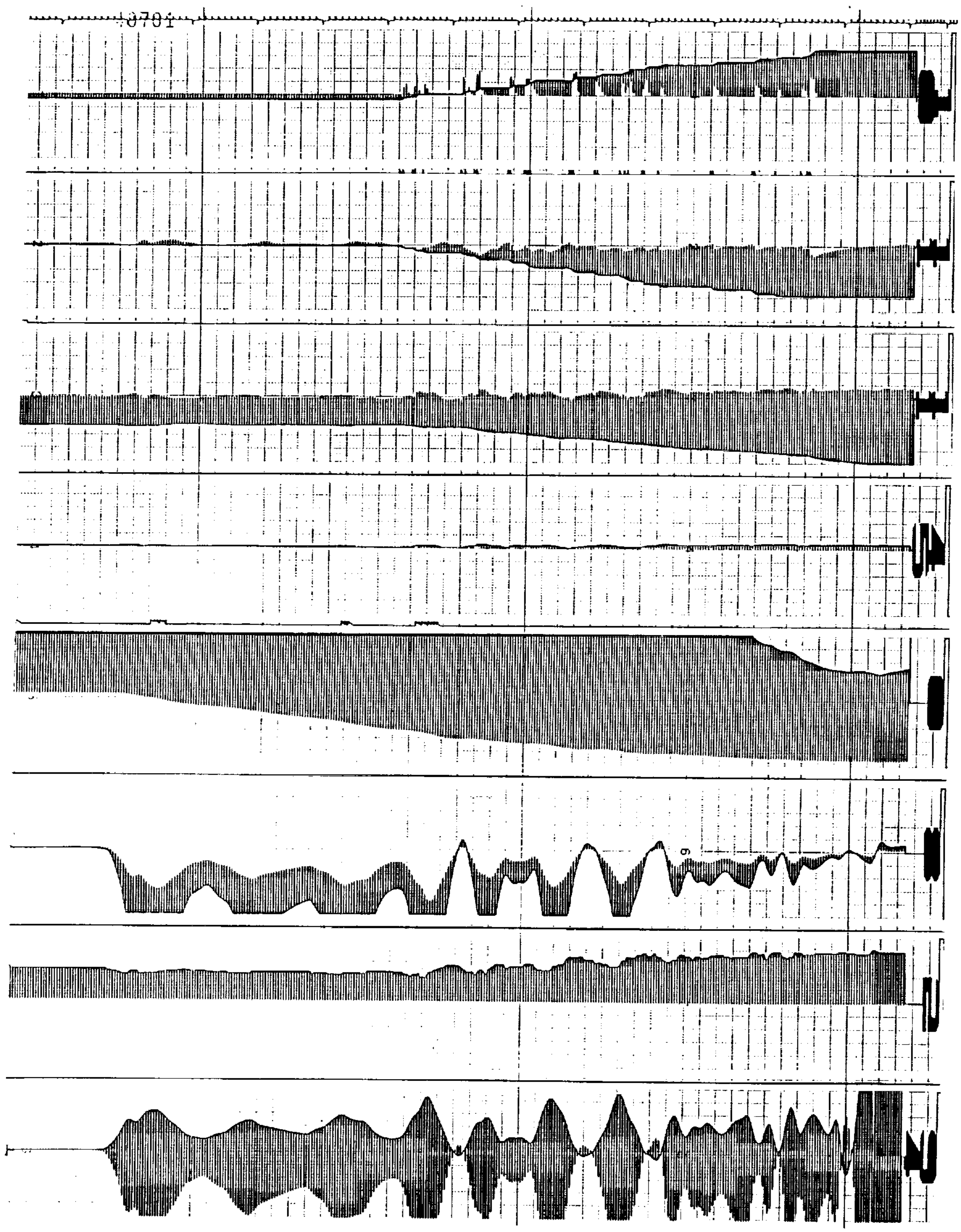

Figure B-13. Programmed flap (run 115).

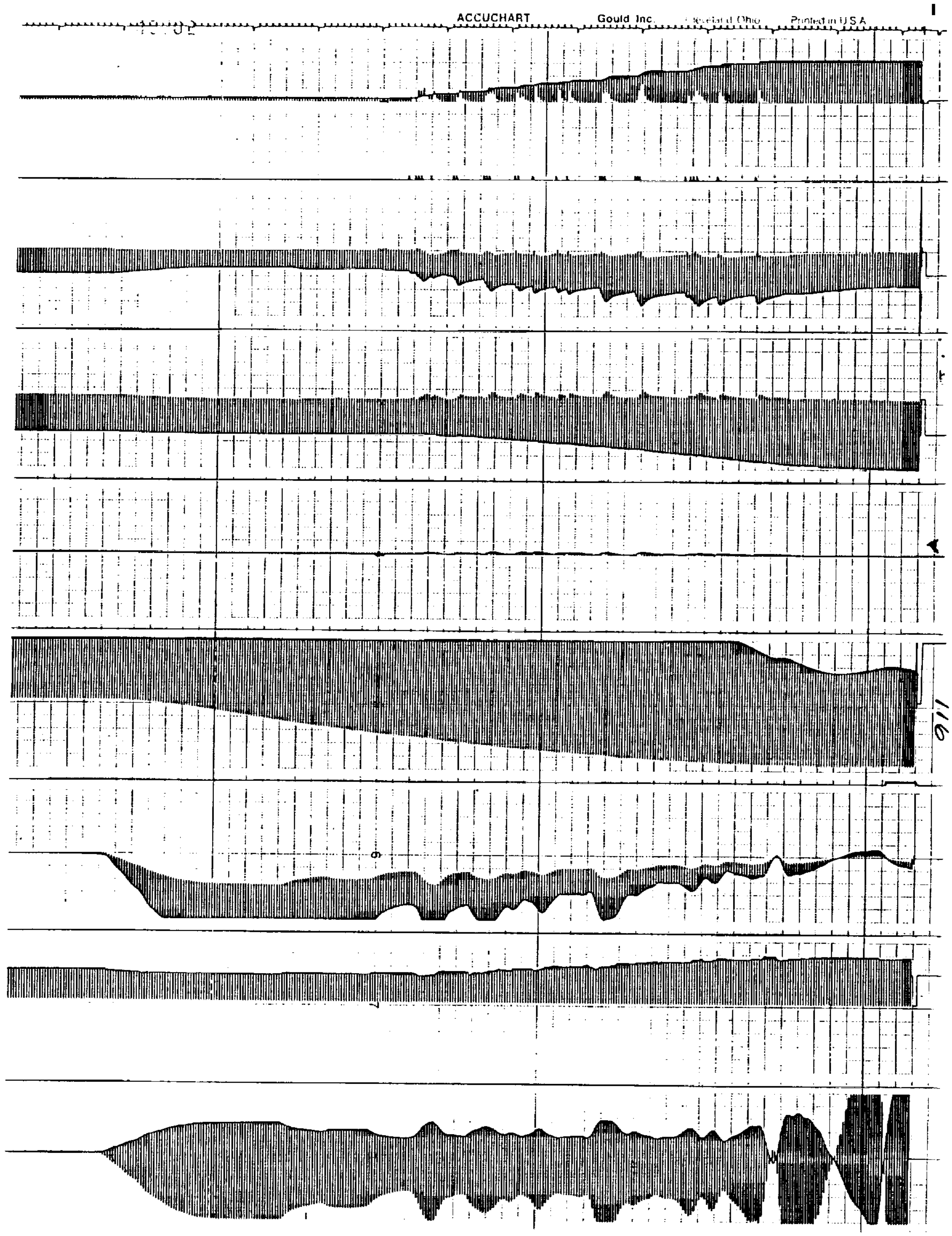

Figure B-14. Geared flap on the beep (run 116).

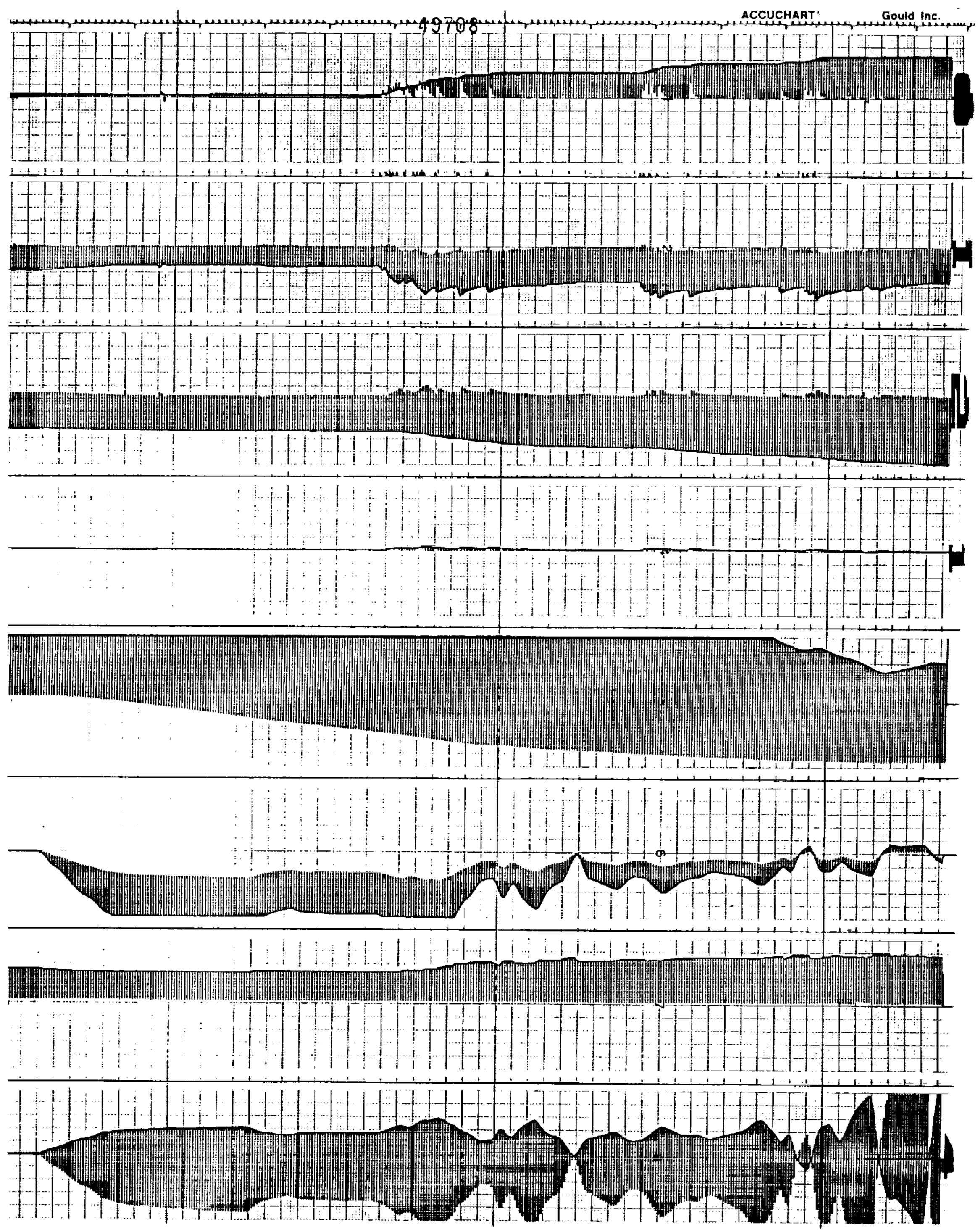

Figure B-15. Geared flap on the stick (run 121).

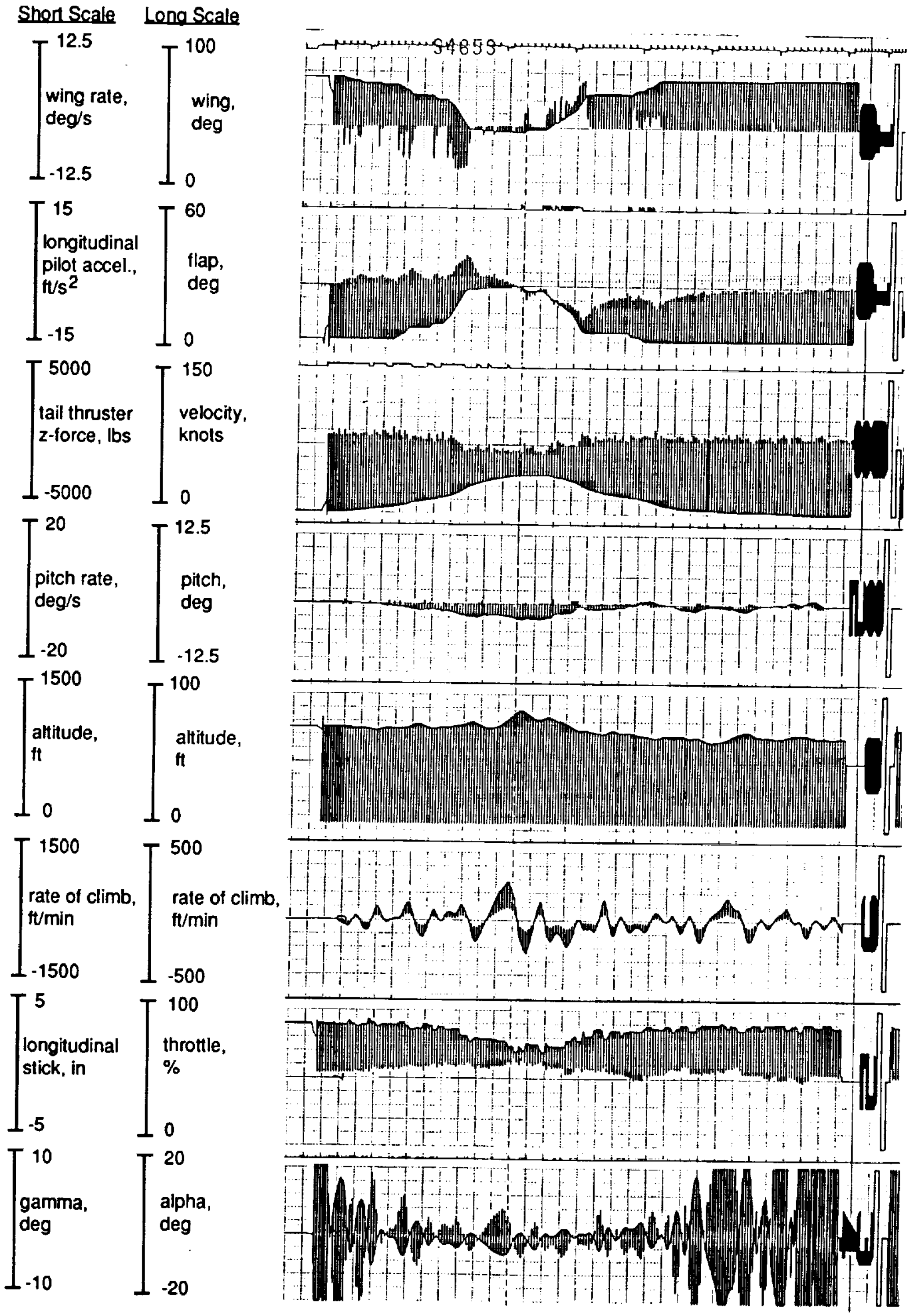

Figure B-16. Programmed flap (run 82).

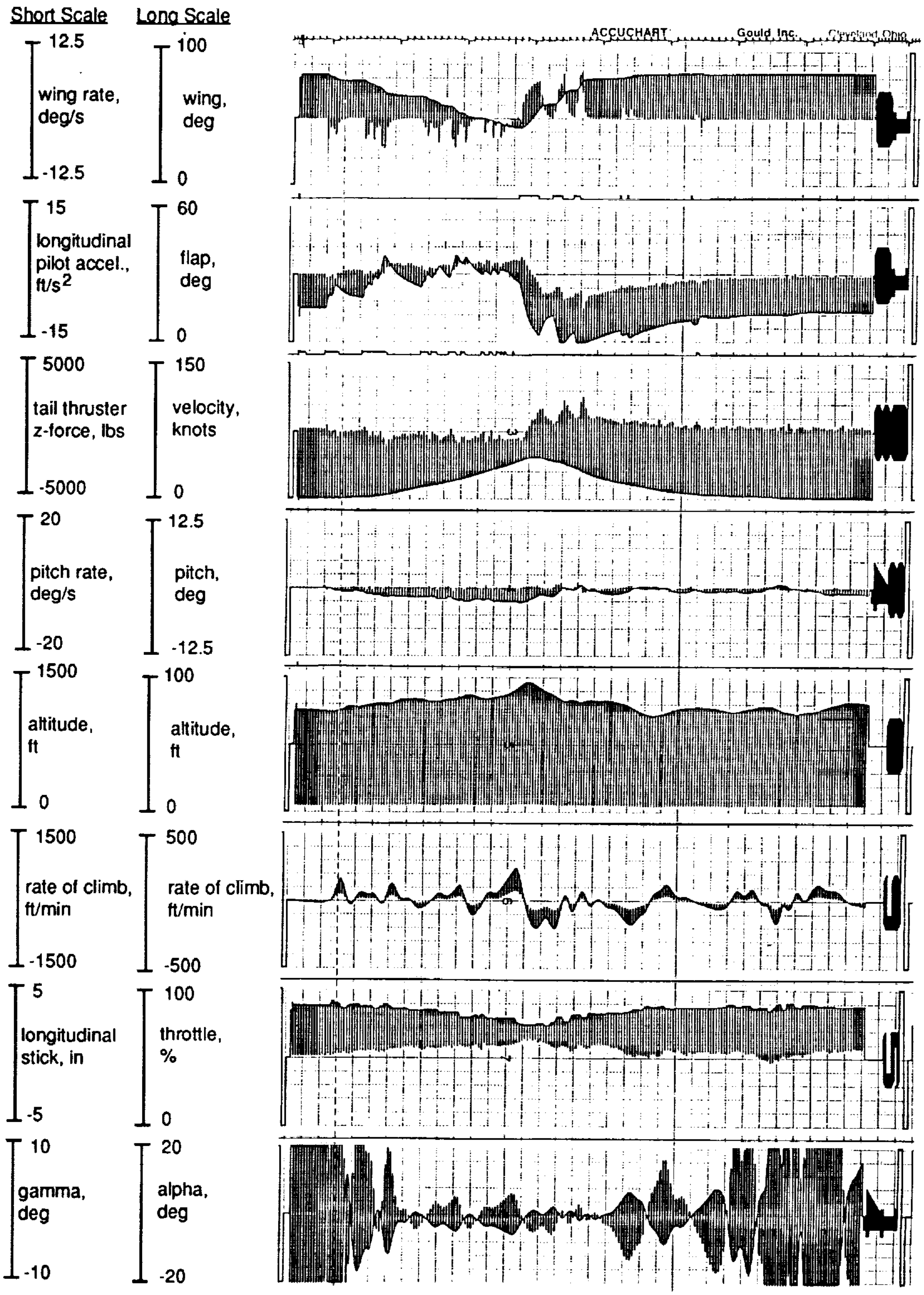

Figure B-17. Geared flap on the beep (run 84).

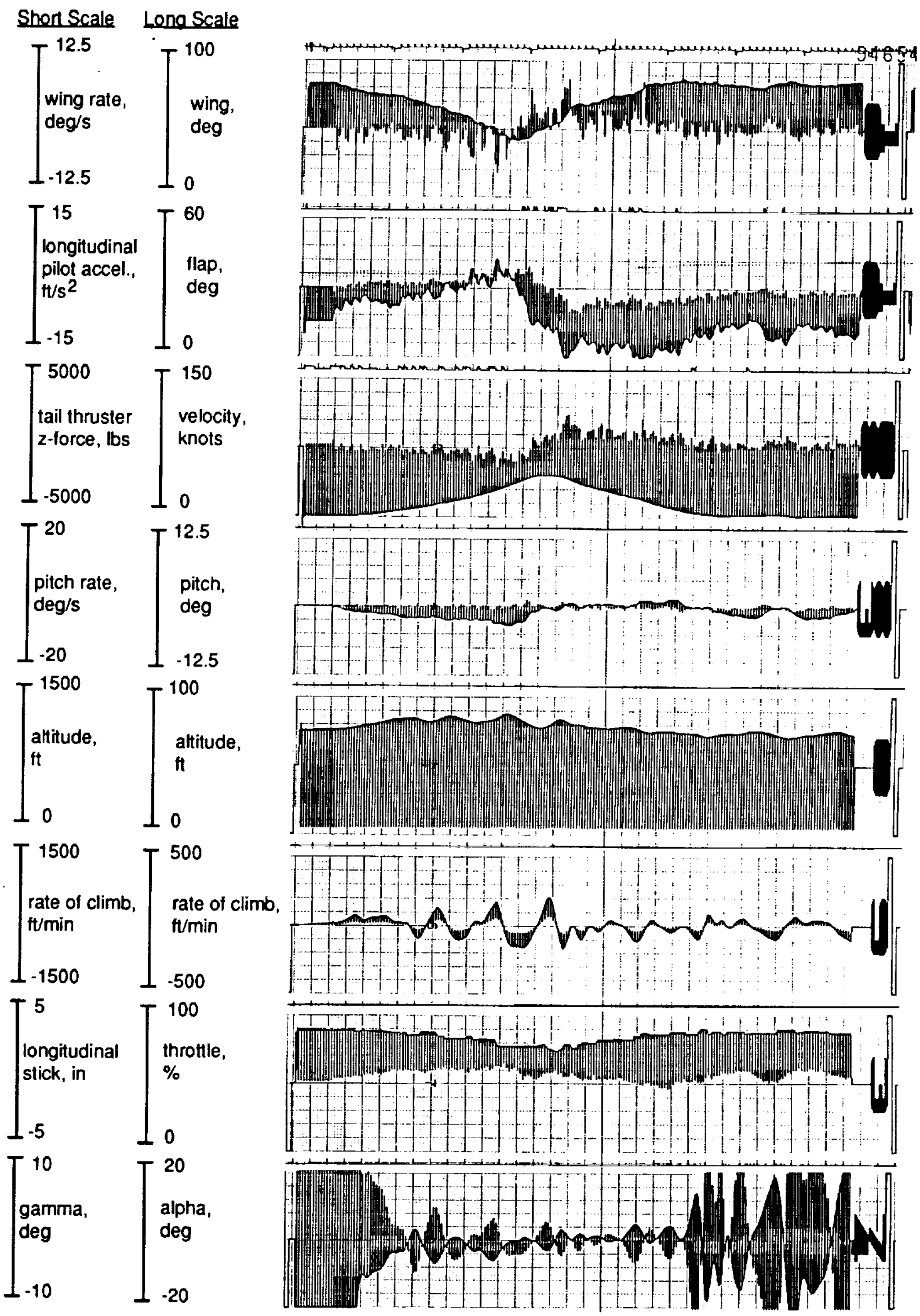

Figure B-18. Geared flap on the stick (run 83).

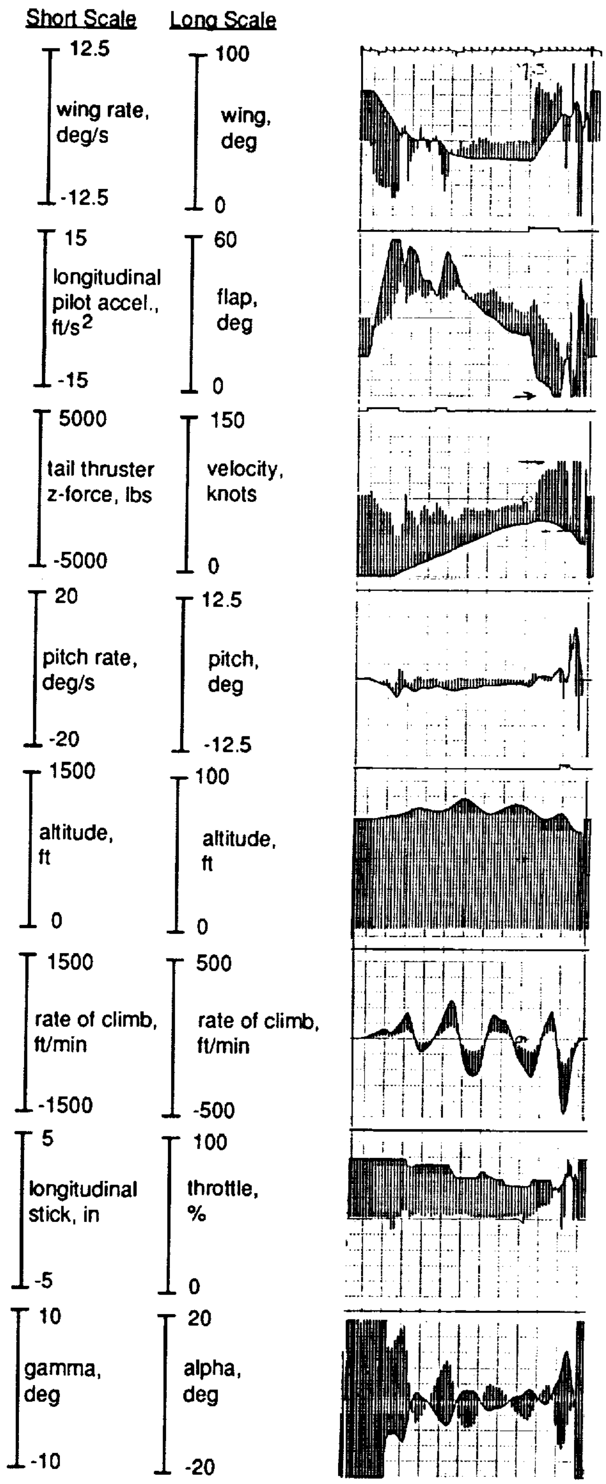

Figure B-19. Geared flap on the stick (run 93, for comparison with run 83; discussed in this report).

Appendix C

The pilot ratings and comments during all recorded runs are documented in the following pages.

Pilot Evaluations

Run no.	Date	Pilot	Task	Flap config.	Pilot rating	Pilot comments
1	10-25-91	Guest	Level inbound	GFB	5	It is easy to maintain level deck. Altitude is the critical parameter. Encountered buffet. Met desired performance standards except for altitude which was adequate performance only.
2				PF	Abort	
3					Repeat	
4					6	Workload increased to maintain level pitch attitude. The power/pitch coupling seems harder to deal with in this configuration. Exceeded desired altitude and pitch performance.
5	10-29-91	A	Level inbound	PF	3	Achieved desired performance. Encountered buffet twice. No hover overshoot, good control predictability. Concentrating on height control and power management. SAS holds pitch well.
6					3	Repeated to get valid showprint data.
7/8			−7.5° approach	PF	2	Slow task; just requires power regulation instead of gross maneuvers. Height control is the most demanding part of the task. Attitude stabilization running real good. Roll damping is still a little low. Lateral axis is not a problem at all.
9/10			Hover station keeping	PF	5	Considerable compensation required for height control. The technique for regulating position is to fix the wing and modulate pitch attitude. Visual cues are somewhat limited.
11				GFS	–	Doing a better job holding position. There is a significant difference between the two configurations. Would extrapolate a rating of 4, but I don't want to rate it until showprint is working.
12			Longitudinal reposition	PF	4	Vertical axis was a little bit oscillatory and demanded attention. No buffet was encountered. Good attitude hold, and good predictability in velocity.
13	10-30-91	Guest	Hover station keeping	GFS	3	Workload was not bad. Adequate performance on altitude, and desired on all other parameters.

Pilot Evaluations (continued)

Run no.	Date	Pilot	Task	Flap config.	Pilot rating	Pilot comments
14	10-30-91	Guest	Hover station keeping	PF	2.5	Felt better with this configuration. Height control was easier.
15				GFB	2.5	Aircraft characteristics were similar to the PF. Met desired performance for all parameters except for position which was only adequate.
16			Longitudinal reposition	GFB	2	No trouble during acceleration part of the task, but still had some trouble during the decelerating part. Met desired performance parameters except for pitch attitude and altitude.
17/18				PF	2	No comments on aircraft characteristics. Did have trouble stabilizing at the end, did overshoot end position. Adequate performance on altitude and pitch attitude.
19				GFS	2	No trouble with it, but I can feel the flap. I liked the configuration. Adequate performance on altitude and pitch attitude. No buffet.
20/21			−7.5° approach	PF	2	During transition hit buffet twice. Didn't overshoot hover position. It wasn't the best approach close in, I had the wing up too far too soon.
22				GFS	2	Tracked altitude better. No buffet was encountered. Did not overshoot hover position. I liked this one better.
23/24				GFB	2	The workload was low and no compensation was required. The approach was better. Met desired performance.
25/26			Level inbound	PF	2	Met desired performance, except for altitude and pitch attitude which were adequate performance.
27				GFB	2	The aircraft characteristics were the same. Met desired performance except for the amount of time in buffet.
28/29				GFS	2	Had a harder time with this configuration. Altitude was barely adequate; encountered buffet.

Pilot Evaluations (continued)

Run no.	Date	Pilot	Task	Flap config.	Pilot rating	Pilot comments
30	10-31-91	A	Level inbound	GFB	4	Desired parameters were met, although buffet was encountered. Attitude control was easy. SAS is good. It was more difficult to predict end point because of non-minimum phase, which affects speed control and is a noticeable and unpleasant characteristic. Improvement warranted for 1) speed predictability toward the end point, and 2) height control.
31				PF	3	Met desired performance. Encountered buffet twice, but it was noticeably less than GFB. Speed predictability at the end point was much better.
32/33/34				GFS	–	Differences noted on the pitch axis, SAS not as good. Deviated from task to study the problem.
35				GFS	5	Adequate performance: overshot the end point, pitch attitude was out of bounds, not happy with the time spent in buffet. Pitch attitude demanded a lot of attention. Power management and height control suffered also. Speed predictability at the end point was not so good.
36	11-4-91	B	Level inbound	PF	4	Hardly used the stick. The short term response to wing beep was a heave response and required coordination with power. Aircraft sensitivity seemed low at the lower speeds. Coupling noticed in wing movement to throttle. Compensation: a lot of lead factor. Primarily mental workload not physical. Minor deficiencies because of heave oscillations and encounter with buffet. Felt the desired performance parameters were met.
37				GFB	5	The heave response to initial wing movement was much better than PF (coupling was not as bad). When flap gets into a limit, it jerks the aircraft a little. Control power was not an issue. At low speeds, the response to a wing movement and to throttle seemed low. Undesirable pitch response as velocity decreases. The pilot lead was less than with the PF, but the time spend in buffet was longer than with PF. Felt the performance was desired to adequate.

Pilot Evaluations (continued)

Run no.	Date	Pilot	Task	Flap config.	Pilot rating	Pilot comments
38	11-4-91	B	Level inbound	GFS	5	Needed the stick initially. Aircraft doesn't seem to slow down. At the flap limits, flap seems to run out of control power. Deceleration predictability seems low. Not as much speed control with wing beep, different correlation than other configurations, doesn't seem right. Buffet time was too long for desirable. The anticipation to stop the beep prior to flap limit to avoid pitch oscillations increased the pilot compensation. Hitting the flap limit leads to pitch oscillations, and increases the rating from "4" to "5."
39			−7.5° approach	GFB	3	Slope intercept was easy. The workload was low. Predictable response to wing movements. The initial response on all control inputs were all good. There was plenty of control power, and sensitivity was good. There was no coupling in any axis. Smooth approach, no buffet was encountered. Felt all the desired performance parameters were met. The workload was mental only, leading the wing movements with power crosschecked with vertical speed.
40				PF	3	Minimal differences from GFB. Minor heave response with wing movements, very minor, more of a feeling. There were no limitations on control power. Small perceived heave coupling to wing movements. No oscillations or buffet encountered. Felt all the desired performance were met. The workload was mental only in the heave axis. Very mild deficiencies. The GFB configuration was slightly better even though both are rated "3."
41				GFS	3	Subtle differences from GFB, not using much stick. Wing movements correlating with power was about the same. No control power limits. Mild oscillations perceived in pitch or z, hard to tell. No buffet. Compensation was not any different than other configurations. Solid on the glideslope.

Pilot Evaluations (continued)

Run no.	Date	Pilot	Task	Flap config.	Pilot rating	Pilot comments
42/43/44	11-5-91	C	Level inbound	PF	4	The vertical axis was a little on the sensitive side. Oscillations were not a problem. Yaw and lateral axis were not a problem ("3"). Longitudinal axis not a problem but a "4;" the end point predictability was certainly a factor, I had to work to end at that point. Desired performance was met.
45/46/47				GFB	5	No coupling oscillations. The pilot workload was fairly high towards the end. Roll and Yaw a "3," in general a "4," but moderately objectionable because of buffet and hence, a "5."
48/49/50				GFS	6	Unable to get the cause and effect of wing change on the longitudinal axis. Control power was not a problem. Throttle was a bit sensitive. Compensation and workload are a factor now, due to the stick changing the wing from where I set it. Predictability at the end point was poor. Desired performance was met except for altitude which was adequate. Did not like configuration.
51			Hover station keeping	GFB	4	Aircraft short term response, sensitivity, and coupling were not a problem. Desired performance requires moderate pilot compensation. I exceeded the longitudinal position limits—performance was less than adequate.
52				PF	4	Almost felt better than GFB, but got blown off at the end. I could not see a lot of difference between the configurations. Workload was about the same. Desired performance was met, except for longitudinal position which was adequate.
53				GFS	3	No aircraft characteristics comments. The pilot compensation was normal, and hover-like. The workload was less than the previous configuration. Would like to call it a "3.5," but I am not allowed. Desired performance was met.

Pilot Evaluations (continued)

Run no.	Date	Pilot	Task	Flap config.	Pilot rating	Pilot comments
54/55	11-5-91	B	Hover station keeping	GFS	3	Used stick inputs only, and made larger inputs than expected to. The response was a little sluggish at first. Did not hit any control power limits, more of a sensitivity issue. Did not see much coupling, especially at this turbulence level. Did see oscillations, as a result of control inputs. Anticipation and lead required, but mainly a matter of staying right on it—high pilot gain. Workload was pretty high to maintain position. Desired performance was met, except for longitudinal position which was adequate.
56				PF	3	Flying with the wing only, easier to judge the drift error. Initially the response of the wing seemed sufficient and predictable. Had lower pilot gain than GFS. Control power and wing rate were not a factor. Sensitivity was good. There was no coupling and really no oscillations due to the aircraft, only in response to gust. Altitude control was much tighter. The workload seemed lower than GFS, no real lead factor was necessary. Felt all the desired performance were met, although I may have drifted too far once on longitudinal position.
57				GFB	4	This configuration is easier using stick for longitudinal position. The short term response seems sluggish but predictable. Control power seemed close to the limits. Sensitivity seemed low for station keeping in turbulence. Did not see much more lead, but workload was up; larger control inputs were required to get a response—predictability was a bit lower. I found the –3° pitch annoying.
58	11-6-91	C	–7.5° approach	PF	3	Sensitive response to power. The demands on the pilot were average, and compensation was normal. Desired performance was met.
59				GFS	3	No change noticed in the aircraft characteristics or in the amount of compensation required. May have noticed a slight increase in the workload. Desired performance was met.

Pilot Evaluations (continued)

Run no.	Date	Pilot	Task	Flap config.	Pilot rating	Pilot comments
60/61	11-6-91	C	–7.5° approach	GFB	4	Lead compensation was required, the predictability degraded. The workload was higher in this configuration, had to stay on top of the task. High pilot gain was required. The desired performance required moderate pilot compensation. Desired performance was met—except for pitch attitude performance which was between desired and adequate.
62/63			Longitudinal reposition	GFB	4	No comments on aircraft characteristics. High pilot gain was required, the pilot lead compensation was heavy into the task. Relatively high workload. Desired performance was met, but pitch attitude performance was between desired and adequate.
64				GFS	4.5	The initial wing response to a pilot input was perceived to be quicker in this configuration. Sensitivity and control power were the same as before. As a result of the quicker wing response, I had to predict more strongly, so that the workload was a bit higher. You don't want a real quick response for this size aircraft, the pilot might like it, but passengers would not want their teeth rattled. Desired performance was met.
65				PF	3	The aircraft short term response is more to my liking. I was able to predict and anticipate the response to my wing position input. In general, it was easier to predict the termination point. Good relationship between cause and effect. Desired performance was met.
66				PF	3	Tried the same run with reduced control power (0.24 rad/sec^2). The task performance did not degrade—maybe with winds or turbulence it would, but without winds it was still OK.
67			Hover station keeping	PF	–	Tried this task at the reduced control power of run 66. I feel the performance is still about the same, and that the same high pilot gain was still required.

Pilot Evaluations (continued)

Run no.	Date	Pilot	Task	Flap config.	Pilot rating	Pilot comments
68	11-6-91	B	Longitudinal reposition	GFB	4.5	I felt like I was moving backwards when I initially beeped the wing. The pitching moment was unnerving when at the flap limit. I perceived a control power limit when I hit the flap = 0 limit. A little adverse coupling with longitudinal command with beep—undesired. Not really any oscillations (minor roll oscillation). The response of the aircraft was a little slow, and you must lead to arrive at the end point at the right speed. Only trouble was with altitude, desired/adequate performance there. The workload was primarily mental to avoid buffet.
69				PF	3	The short term response to a control input was a little jerky, there was a small pitch acceleration, it was a little rougher than GFB. Did not hit any flap limits. Throttle sensitivity seemed a little low. All responses were predictable. Compensation was associated with anticipating the heave response to wing movement. The workload was mental, and easier than GFB, I could maintain level attitude easier and concentrate on throttle better. I would recommend a more sophisticated SAS to avoid uncommanded altitude changes. Desired performance was met.
70				GFS	3	The short term longitudinal aircraft response to a wing movement was the same as the GFB—initially backwards, and slow to accelerate at first. I did not see any coupling or oscillations. Control power was not an issue. Compensation was associated with leading the heave response with throttle. I did not use the stick very much. Height control was mildly unpleasant. It is a "3," but the workload was a little different than PF. Desired performance was met.
71/72	11-7-91	D	−7.5° approach	GFS	4	There was a vertical up response when beeping the wing. Control power, sensitivity, and oscillations were not an issue. Coupling noticed between wing and vertical altitude. The workload was moderate, and mental not physical. Desired performance was met.

Pilot Evaluations (continued)

Run no.	Date	Pilot	Task	Flap config.	Pilot rating	Pilot comments
73	11-7-91	D	−7.5° approach	PF	5	The heave response to a wing movement was more exaggerated than GFS. Control power was not an issue, I was getting the response out of the throttle that I needed. Lateral/directional control was no problem. The coupling between wing and vertical heave was more exaggerated than GFS. I used the throttle more, and the compensation required was higher. The workload was also a little higher. Desired performance was met. I felt buffet once, but it was less then 5 seconds.
74				GFB	3	I felt the glideslope tracking was the tighest so far. The response to a control input was a little smoother, certainly smoother than GFS and PF. The sensitivity was appropriate. Coupling was noticed between wing movement and vertical. The workload was associated with staying on the glideslope. This was the best of the three approaches in my opinion. I think the GFS may have had less control activity, but I did better with GFB; PF was not a contender. Desired performance was met. At sometime we need to look at all of these with turbulence—performance will degrade, but this was quite good.
75/76			Level inbound	PF	4.5	The technique used was small beeps, just a few degrees at a time. Coupling was noticed between wing movement and vertical. There were no sustained oscillations. The compensation required to maintain altitude was significant. I would like to see less displacement in height with wing changes—I was working pretty hard to maintain altitude. Desired performance was met; maybe altitude was desired to adequate.
77				GFB	4	Less heave response to wing movements, improvement over PF, especially during the initial part of the task. Configuration seemed a little smoother. Roll, yaw, and pitch were OK. The workload was reduced over PF, however, I was still flying through buffet. I felt all the desired performance were met.

Pilot Evaluations (continued)

Run no.	Date	Pilot	Task	Flap config.	Pilot rating	Pilot comments
78	11-7-91	D	Level inbound	GFS	4	Similar short term response to GFB, and with wing/throttle coupling. Both geared flap configurations were an improvement over PF. Control power and sensitivity were not a factor. The pilot compensation required was similar to GFB. Time spent in buffet was similar to GFB. The big task was holding altitude, but it was less work than with PF.
79			Hover station keeping	GFB	3	I felt gusts in all three directions—yaw was not a problem, and I can handle lateral and longitudinal. I was always working the throttle to control vertical position. I used the pedals, lateral and longitudinal stick and lots of throttle, but no wing. All the responses were appropriate. Control power, sensitivity, coupling and oscillations were not an issue. The workload and pilot compensation were moderate for a very turbulent condition and associated with maintaining position. The lateral displacements were quite small, the larger displacements were longitudinally and vertically. Desired performance standards were achieved. Without turbulence, the aircraft would be very stable.
80				PF	5	I perceived definite differences. The short term response seemed less appropriate and less adequate than GFB. The displacements due to turbulence required more throttle inputs. Control power was not an issue. No oscillations were encountered. The workload was higher, almost seemed like a higher turbulence level. I also feel that the task performance went down, especially with altitude.
81				GFS	4	The initial response to vertical was the same as GFB. The flap is definitely helping compared to the other two configurations. Coupling and oscillations were not an issue. The pilot compensation and workload decreased compared to PF, although the workload was certainly there. I achieved the desired performance, but the workload was up a bit from GFB. It was a toss up between a "4" and a "3," but I give it a "4" because of control activity—I seemed to get more vertical displacement to gusts.

Pilot Evaluations (continued)

Run no.	Date	Pilot	Task	Flap config.	Pilot rating	Pilot comments
82	11-8-91	D	Longitudinal reposition	PF	4	Short wing movements resulted in vertical displacement. I noticed that wing movements of about 20° at a time gave smoother acceleration; a lot better than short little wing movements and I held altitude better. Control power and sensitivity were not issues. Noticed coupling between wing and throttle, as always. The workload was mostly associated with height control and a little bit on longitudinal acceleration/deceleration. Desired performance standards were met.
83				GFS	4.5	The vertical ride was just a little bit bumpier. I perceived a slight increase in vertical response to wing movement. Control power was adequate for vertical axis, and not an issue in the others. The workload was a tad more, not as smooth as PF. I perceived the desired performance standards were met.
84				GFB	4	This was an improvement over the GFS, the response to a wing movement was not as abrupt. Control power was not saturated. Coupling was noticed in wing to vertical, as usual. No oscillations were encountered. The ride quality was an improvement to GFS, but not as smooth as PF. The workload was associated with throttle management to maintain altitude. Overall, desired standards were achieved.
85/86			Hover station keeping–full turbulence	GFB	3	I was getting healthy disturbances. The short term response of the aircraft was certainly adequate to maintain position. Sensitivity was OK. Control power was not an issue. Got no significant coupling since I was not moving the wing. This one is hard to call because of such outrageous conditions. Considering the task and the degree of turbulence, the workload was between minimal and moderate, but I can't rate between levels. I think this configuration is the best to meet the desired performance.

Pilot Evaluations (continued)

Run no.	Date	Pilot	Task	Flap config.	Pilot rating	Pilot comments
87/88	11-8-91	D	Hover station keeping–lateral turbulence off	GFB	2.5	The workload certainly went down. Although the longitudinal gusts seemed exaggerated. I kept a tighter position than with full turbulence. Control power and sensitivity were good. The workload definitely went down by cutting the lateral turbulence. There were periods when I was very relaxed. All the desired performance standards were achieved.
89/90			Hover station keeping–no turbulence	GFB	1.5	That certainly was no big deal. Control activity was very different—almost missing entirely in some parts. The control activity was so low that there is not much to say. The control inputs were very small, very reduced. The demands on the pilot were very low. In the real world you are never hovering and holding a tight position.
91		E	Longitudinal reposition	PF	4	There was quite a bit of lag in the initial longitudinal response to the wing beep. The short term response was not very predictable, and required virtually continuous throttle inputs. The initial and final wing configuration requires a lot of regulation. The lateral displacement wasn't very tight, but it's not a performance issue. Maintaining altitude was the most difficult performance standard to achieve. There was poor height predictability so compensation was required, and the workload was mental. The desired performance was achieved, but the compensation was more than I would have liked, and for that reason I give it a "4."

Pilot Evaluations (continued)

Run no.	Date	Pilot	Task	Flap config.	Pilot rating	Pilot comments
92	11-8-91	E	Longitudinal reposition	GFB	7	The nonminimal phase response was on the order of 5 seconds before the aircraft responded in the direction I wanted. The heave response was very unpredictable. The middle portion of the task was not too demanding. There was some coupling between pitch and beep which added to the mental and physical workload. Altitude was exceeded in the initial and final phase of the task. Pitch attitude was exceeded because of pitch coupling and while trying to capture the hover position. There were several end position overshoots; got into a divergent PIO trying to correct the problem; changed technique to set wing for hover and captured final position with attitude, then exceeded desired attitude performance standards. Control power and sensitivity were OK.
93				GFS	10	During practice before this run, I excited a pitch PIO and got out of control. It happened again during this run. The technique used is to aggressively move the wing, "bringing my Harrier technique into the table." From the pilot report immediately after run: The initial response to a wing beep is nonminimum phase as evident by rearward translation prior to forward motion. During early translation as speed is increasing (~10-15 knots) a pitch bobble occurs that diminishes as speed reaches steady state. This pitch bobble is a result of countering the pitch-wing coupling and is a momentary PIO that diminishes as speed increases. Height regulation during the initial portion of the translation is difficult because the heave response to throttle is not predictable. Mid translation is generally satisfactory. Decelerating technique required continuous aft beep because an overshoot situation was perceived to be developing; as power was increased to account for the loss of wing lift, the pitch power coupling response was apparent and I countered with stick input; the response to stick input was a rapidly developing, divergent PIO that resulted in loss of control after two oscillations.

Pilot Evaluations (continued)

Run no.	Date	Pilot	Task	Flap config.	Pilot rating	Pilot comments
94	11-8-91	E	Longitudinal reposition	GFS	Level 3	Pitch control power increased from 0.3 rad/sec^2 in run 93 to 0.6 rad/sec^2. Pitch problem damping itself out, and height problem sorting itself out, but it was easier to land than to get to a stable hover and deal with the nonminimum phase shift problem.
95	11-12-91	E	Hover station keeping	PF	4	Height control response to throttle was not that predictable, and required multiple throttle inputs. I kept attitude constant, and used wing beep for longitudinal positioning; this response was also not that predictable. I felt it was a highly iterative process to control height and position. Control power and sensitivity were fine; no coupling or oscillations were encountered. I think the workload was very high. I feel that pitch attitude and lateral attitude are parameters of interest and should be part of the performance standards. Desired performance standards were achieved with moderate compensation.
96				GFB	4	The technique used was pitch attitude for longitudinal positioning. The response to height control was the same as for PF. No limits were noted for control power. The stick sensitivity seemed low. There were no coupling or oscillations. The workload was larger for lateral positioning, but less for longitudinal positioning, and about the same for height control maybe less (all these compared to PF).
97				GFS	4	The workload was similar to GFB, but larger for longitudinal and lateral positioning. Bank amplitudes were large, had a lot of roll activity. The sensitivity to stick input seemed low. Desired performance was achieved.

Pilot Evaluations (continued)

Run no.	Date	Pilot	Task	Flap config.	Pilot rating	Pilot comments
98	11-12-91	E	−7.5° approach	PF	4	Flight path control was difficult because it was a mental exercise deciding what rate of climb was desired for each wing angle. The predictability factor added to the difficulty. Heading control and keeping attitude constant were not a factor. Sensitivity was not a problem. There was coupling with pitch but it was so small, it was not really coupling. It was a long, slow approach but still alright. I did require a series of beeps (and you can feel them), and I wonder if passengers would like it. All the desired performance standards were met.
99				GFB	4	The workload was primarily associated with flight path control, you still needed different rates of climb for each wing angle, and this scheduling added to the workload. Objectionable pitch coupling with wing beep. Desired performance standards were met. No control power limitations. Sensitivity was OK, and no oscillations were encountered.
100				GFS	4	This was the same as the last configuration except for the last 10 feet. I was careful to set the wing at 83° (hover wing angle), and finished hover with the stick. Workload—same comments as previous case. Desired performance was achieved. Same workload, same rating.
101			Level inbound	PF	5	A lot of compensation was required to anticipate the heave response to wing changes: power change, let aircraft settle, then move the wing again. The predictability of the heave response was not that great, and required multiple power inputs. I didn't have a feel for the deceleration profile. Performance was in the desired boundaries. The workload was associated with height control. Control power was not an issue. Sensitivity was about right. There was a minor pitch power coupling, but no oscillations were encountered.

Pilot Evaluations (continued)

Run no.	Date	Pilot	Task	Flap config.	Pilot rating	Pilot comments
102	11-12-91	E	Level inbound	GFB	5	A little less heave response than PF, but the workload was still intense. The heave response predictability was not that good, and required continuous throttle inputs. I tried to get the wing at 83° quickly, and finished acquisition of the end point with pitch attitude changes. The desired performance was achieved. It's a "5" because of height control compensation.
103				GFS	5	During the practice I encountered a height control PIO, and I saw the nonminimum phase response which I had not seen in approaches before. During this run I decelerated more aggressively than in practice to get the configuration more in control—worked out pretty well, but altitude was outside of bounds. The workload was quite difficult for the same reasons. It was difficult to get a handle on the correct deceleration profile. The latter portion of task was very slow and drawn out. Buffet I couldn't do anything about, but it was less than 3 seconds each time.
104				GFS	–	Experimented with new gains in control system. Too sharp edge on the pitch attitude response.
105/106				GFS	–	More experimentations with gains. Response to stick input a little bit abrupt. Added flap overtravel. Pilot thought it was much improved.
107/108			Longitudinal reposition	GFS	5	Back to baseline gains in control system, and the same as run 93 except pitch control power is now permanently set at 0.6 rad/sec^2. The response to initial wing movement was the nonminimum phase response. Poor predictability of height response to wing movement, the pilot anticipation was high. The workload was along the height axis. There was anticipation along the longitudinal axis in terms of the decelerating profile. The task was accomplished in two stages: continuous beeping from 40°–75°, the final portion was slow and deliberate. Well under control. Got a little aft drift at the final hover.

Pilot Evaluations (continued)

Run no.	Date	Pilot	Task	Flap config.	Pilot rating	Pilot comments
109	11-12-91	E	Longitudinal reposition	GFS	5	Experimented with gain changes again. The initial response to a wing movement had a lag of about 9 sec, which makes longitudinal positioning with wing highly unpredictable. The workload was associated with height control and anticipating the deceleration profile. Easier acquisition of the hover point.
110/111	11-13-91	A	Longitudinal reposition	PF	3	Height and height rate cues demanded a lot of attention. Speed control was predictable, and was able to converge on the end point. Had to coordinate power, wing tilt, and speed to control height. A bothersome feature was a pitch up response to a wing down movement, but this did not cause any control problems. Achieved the desired performance standards, except I did overshoot the hover position just a little bit, did not overshoot in practices, though. I am really split between a "3" and a "4."
112				GFB	4.5	Delay in the initial speed response of the aircraft, poor predictability of speed and position control because of nonminimum phase response. Height axis was easier to control than PF. Performance objectives were met.
113/114				GFS	4.5	Looks much the same as GFB. Had no need for the stick, so the wing on stick features were not at play. Met the desired performance. Longitudinal control of the aircraft was not predictable. Had a reversal in pitch attitude after the beep request. This pitch response cue combined with the longitudinal acceleration can produce a potentially confusing situation. The vertical axis was fairly easy.

Pilot Evaluations (continued)

Run no.	Date	Pilot	Task	Flap config.	Pilot rating	Pilot comments
115	11-14-91	A	–7.5° approach	PF	3	This task was quite simple, there were no disturbances. The glideslope acquisition was simple, I had a constant speed setting, and attitude was fixed, at 400 ft started to decelerate and I only had to regulate power and tilt the wing to maintain the glideslope. When I started the deceleration the workload noticeably increased. No aircraft characteristics were bothersome and I met the desired performance objectives. It was a long and steady decelerating approach, like a helicopter. If improvements were made, it would be in the height axis. Noticeable workload to bring it all together at the end point.
116				GFB	3	The workload was fairly low. The desired performance was achieved. It was a very slow and deliberate deceleration, and it was easy to judge the final arrival at the hover point. Although it takes the aircraft a little longer to finally arrive at hover, otherwise it was a lot like PF. I was able to keep the electronic guidance in the middle all the way, so height control was easier in this configuration.
117/118						Simulator problems.
119/120						Studying flap limits.
121			–7.5° approach	GFS	3	This run looked the same as GFB—I made no use of stick for control so the wing on the stick feature was not called into play. Identical aircraft characteristics as GFB. Desired performance was achieved. Low effective or apparent speed damping.
122/123			Hover station keeping	GFS	5	The visual cues to maintain position are limited. It is easy to drift with nose up or down to correct for gust. I am controlling position with attitude, but attitude is affected by gusts. There were sharp angular accelerations due to gusts, and somewhat uncomfortable gradients. I felt I achieved the desired performance, except for the longitudinal position limits.

Pilot Evaluations (continued)

Run no.	Date	Pilot	Task	Flap config.	Pilot rating	Pilot comments
124/125	11-14-91	A	Hover station keeping	PF	5	The technique I used to maintain position was pitch attitude, leaving the wing alone. I experienced significant pitch attitude changes. So I had a requirement for larger pitch inputs—the control effort longitudinally increased in terms of force applied to the stick. The large pitch attitudes were noticeable and objectionable.
126/127				GFB	5	The technique I used to maintain position was pitch attitude. I did not use the wing, and there were no wing movements due to gust.
128/129					7	I controlled position with pitch attitude fixed, and used only the wing. The major deficiency was the nonminimum phase response: initial response to a wing movement was in the wrong direction, and resulted in oscillatory and divergent characteristics. The demands on the pilot were higher with this technique.
130				PF	4	I controlled position with pitch attitude fixed, and used only the wing. The visual perception of position error was better. This technique is preferable for PF. The workload was reduced. I was able to predict the longitudinal speed response better.
131		F	Level inbound	PF	4.5	I used the stick very little. There was a quick response of speed as far as wing tilt goes. I used the throttle to maintain altitude, and wing tilt to maintain forward speed. There were definite tendencies to PIO in the vertical axis. I felt I achieved all the desired performance.
132				GFB	5	The short term response to wing movements compare to PF was sluggish, but the coupling with altitude was not as bad. All the work was with power, controlling altitude. Anticipation was required with power for wing movements. I achieved most of the desired performance; altitude got away because of buffet.

Pilot Evaluations (continued)

Run no.	Date	Pilot	Task	Flap config.	Pilot rating	Pilot comments
133	11-14-91	F	Level inbound	GFS	5	Not a whole lot of change from GFB. I did not use the stick at all. I experienced the same coupling/restrictions with altitude, power, and buffet. I had frequent physical throttle movements as it was coupling with wing. Again, I lead with power. I exceeded desired altitude and buffet time.
134			Hover station keeping	GFS	5	I used stick movements for position control. Pitch attitude response was good, but position over the ground was delayed. I had to lead to compensate for the delay. I used no wing tilt at all, so there was no coupling. I did get into a real damped oscillatory movement which took lots of mental concentration to get out of it. The workload was physical, using power for altitude control. I achieved desired to adequate performance.
135				PF	5	I used a combination of wing and stick for maintaining position. The initial response had about a 0.5–1 second delay before you saw any movement. Not much coupling noticed. Experienced slight oscillation laterally. Got into a noticeable longitudinal PIO, and I had to guess when to input control to take it out. Performance was desired except for longitudinal position.
136				GFB	4.5	The short term response was not much different from PF. Although the delay to a wing movement was still there. There was also a lag of about 0.5–1 second from stick movement to lateral response. The compensation was physical—beep switch to maintain position, and power lever to maintain altitude. Altitude performance was desired to adequate.
137/138		B	Level inbound	GFS	6	There was an undesirable pitch response at the flap limit. Looks like I saturated the flap, around 30 knots. Encountered a lot of buffet. There were heave oscillations. There was a lot of lead required to correct for heave response and to avoid buffet. Except for buffet, the performance was within the desired boundaries.

Pilot Evaluations (concluded)

Run no.	Date	Pilot	Task	Flap config.	Pilot rating	Pilot comments
139/140	11-14-91	B	Level inbound	GFS	6	The flap limit pitch oscillations fixed. I didn't see that much difference from the last configuration. You have to either control altitude or buffet just like before. The short term response was the same as before: beep input resulted in heave response, and power was used to control heave response and buffet. I used very little stick. Encountered height control oscillations. There was a really tight loop in anticipating with throttle to avoid buffet, fine tuning the throttle to minimize buffet. Time in buffet was very objectionable, but tolerable.

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13. ABSTRACT *(Maximum 200 words)*

A two phase piloted simulation study has been conducted in the Ames Vertical Motion Simulator to investigate alternative wing and flap controls for tilt-wing aircraft. This report documents the flying qualities results and findings of the second phase of the piloted simulation study and describes the simulated tilt-wing aircraft, the flap control concepts, the experiment design and the evaluation tasks. The initial phase of the study compared the flying qualities of both a conventional programmed flap and an innovative geared flap. The second phase of the study introduced an alternate method of pilot control for the geared flap and further studied the flying qualities of the programmed flap and two geared flap configurations. In general, the pilot ratings showed little variation between the programmed flap and the geared flap control concepts. Some differences between the two control concepts were noticed and are discussed in this report. The geared flap configurations had very similar results. Although the geared flap concept has the potential to reduce or eliminate the pitch control power requirements from a tail rotor or a tail thruster at low speeds and in hover, the results did not show reduced tail thruster pitch control power usage with the geared flap configurations compared to the programmed flap configuration. The addition of pitch attitude stabilization in the second phase of simulation study greatly enhanced the aircraft flying qualities compared to the first phase.

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