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S-67 AIRCRAFT FEEL AUGMENTATION SYSTEM FLIGHT EVALUATION

By

Sean J. O'Connor
Donald W. Fowler

August 1972

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

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Subjective reactions of contractor test pilots, combined with flight test results, indicated that a satisfactory load factor force gradient was 18-25 pounds per g. Furthermore, this nearly constant force gradient was insensitive to changes in airspeeds, collective setting, or attitude during maneuvers.

The S-67 was also evaluated by U. S. Army and NASA test pilots. Two flights of equal duration were made by each pilot, one flight with FAS and one flight without FAS. The flight evaluation resulted in the following conclusions: (1) The pitch FAS provided relatively constant stick force per g. (2) The failure characteristics resulting from intentional hardovers were very mild. (3) The recommended load factor force gradient is 10-15 pounds per g. (4) The stick force per g increased pilot confidence and reduced the need for concentration on the load factor indicator. (5) The stick force per g in the cyclic, combined with the collective stick shaker, was a step toward achieving a "heads-up" maneuvering capability. (6) The thumbwheel position trim system is an advance over the conventional "beeper" trim system.

Details of illustrations in
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S–67 Aircraft						
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Stick Force						
Control Sensitivity						
Stick Trim System						
Control Harmony						
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The program was a flight investigation of a feel augmentation system (FAS) installed in the S-67 winged helicopter. This program is one of four flight investigations conducted on the S-67 winged helicopter. The other three flight investigations were concerned with a stabilator, speed brakes, and aircraft maneuverability.

The FAS enhanced the maneuvering capability of the S-67. This force-feel control system, with its nearly constant force gradient (stick force per g varied from 18 lb/g at 100 kt to 25 lb/g at 170 kt), enables a pilot to maneuver the S-67 aircraft more confidently and precisely. Moreover, the collective stick shaker portion of FAS, with its warning of increased rotor loads, permitted more pilot attention outside the cockpit. The thumbwheel position trim system was an improvement over the conventional "beeper" trim system. The failure characteristics of the FAS were very mild.

The report has been reviewed by this Directorate and is technically correct.

This program was conducted under the technical management of Mr. R. C. Dumond of the Applied Aeronautics Division.

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SER-67009

By

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Prepared by

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FOREWORD

This report presents the background and results of an investigation of the Feel Augmentation System (FAS) in the S-67 aircraft. FAS provides "force feel" in the pitch and roll controls, and a stick shaker in the collective control. This program is part of a four-phase investigation of the flight characteristics of the S-67 aircraft as a representative high speed winged helicopter design. Evaluation of the stabilator, dive brakes, and aircraft maneuverability is also part of the flight investigation of the S-67 aircraft.

The work was performed by the Sikorsky Aircraft Division of United Aircraft Corporation for the U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, under contract DAAJ02-71-C-0034, Task 1F163204D15704. Mr. R. C. Dumond was the Army's technical representative.

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LIST OF SYMBOLS

A_p	actuator piston area, in.^{2}
A_T	lateral trim position command, in. (or percent)
B_T	longitudinal trim position command, in. (or percent)
B_{1_s}	longitudinal stick position, in. (or percent)
F	pitch FAS actuator output force, lb
i	current to pitch FAS valve, ma
K_a	gain of actuator pressure loss due to actuator motion, psi/in.^{3}/sec
K_α	yoke tilt feedback gain, ma/deg
$K_{\dot{B}_{1_s}}$	pitch FAS damper gain, lb/in./sec
$K_{\Delta B_{1_s}}$	pitch FAS spring gain, lb/in.
$K_{\dot{\theta}_f}$	pitch FAS fuselage pitch rate gain, lb/deg/sec
K_v	pitch FAS actuator valve gain, psi/ma
L_y	moment arm for force on yoke, in.
M_s	equivalent mass of longitudinal control stick and linkage, lb-sec^2/in.
M_y	equivalent inertia of yoke, lb-sec^2/in.
n_z	load factor, g
P	pitch FAS servo valve output pressure, psi
x	pitch FAS actuator displacement, in.
V	airspeed, kn

α	yoke tilt angle, deg
Δ	difference or change of a parameter
Σ	summation of a parameter
$\dot{\theta}_f$	fuselage pitch rate, deg/sec

Subscripts 1 and 2 denote channels 1 and 2 for the dual pitch FAS

INTRODUCTION

The Feel Augmentation System (FAS) replaces the conventional helicopter position feel control system with a force feel control system. Control inputs are made by applying a stick force rather than a displacement, and the pilot can correlate the force with the resultant maneuvering situation of the aircraft. Since the force per g of load factor is invariant with airspeed, the pilot should be able to perform maneuvers more precisely and more confidently than with a displacement system. By means of a collective stick shaker, the FAS also warns of the onset of increasing rotor control loads.

A FAS was first developed on the CH-53 helicopter in 1968.[1] Further development flight testing done in 1970 showed sufficient improvement of maneuvering characteristics to justify a test on the S-67 helicopter.[2] The result of these development flight programs was that neither a force proportional to normal acceleration (bob weight) nor a spring force that varies with dynamic pressure (q-spring) would provide adequate maneuvering feel for a helicopter. Both the bob weight and q-spring systems have excessive force variations when collective inputs are made. In addition, the q-spring gives forces that are not proportional to load factor during rolling reversals and when large changes in airspeed or attitude occur. However, it was shown that a force proportional to a combination of aircraft pitch rate, stick deflection and stick rate gave satisfactory maneuvering feel.

The CH-53 FAS research program evaluated the attributes of a FAS for a heavy, high-speed transport helicopter. Additional research was required to evaluate possible improvement attributable to FAS in the handling qualities of a medium-weight high-speed attack helicopter. Some of the questions to be answered in the S-67 FAS program were:

1. What are the in-flight failure characteristics of the system?

2. What is the best force level (lb/g) for the S-67?

3. Does the FAS concept improve the maneuvering handling qualities of an attack helicopter?

4. Is the position trim system superior to the conventional rate trim?

5. Does the collective stick shaker permit the pilot to provide for adequate wing/rotor load sharing?

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[1]O'Connor, Sean, MANEUVERING CONTROL FORCE FEEL IN THE PITCH CYCLIC CONTROL OF A CH-53A HELICOPTER, SER-65887, Sikorsky Aircraft Division of United Aircraft Corporation, Stratford, Connecticut, September 1968.

[2]O'Connor, Sean, FEEL AUGMENTATION AND SENSITIVITY CONTROL IN HIGH SPEED HELICOPTERS, Preprint 542, Presented at the 27th Annual National V/STOL Forum of The American Helicopter Society, Washington, D. C., May 1971.

A research program, sponsored by the Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory was conducted to answer these questions. The overall objective was to determine the advantages FAS offers for future attack helicopters capable of high speed and improved maneuverability.

SCOPE OF PROGRAM

A research flight test program evaluated the effects of FAS on the handling qualities of the Sikorsky S-67 helicopter. The program consisted of three parts: (1) establishing safety of flight if FAS malfunctions, (2) developing best FAS system gains for maneuvering, and (3) demonstrating FAS to U. S. Army and NASA test pilots and evaluating the S-67 with and without FAS. Parts (1) and (2) were completed in 5½ hours of flight time. Part (3) was completed in an additional 5½ hours of flight time. The nominal aircraft loading condition used throughout the tests was:

Loading Condition	Gross Weight (lb)	CG Location (in.)	Stabilizer Bias Angle (deg)
1	17,650	269	2.5 leading edge up

Table I lists the primary flight conditions and maneuvers employed in the flight test, along with FAS characteristics that were evaluated.

Safety of flight testing was conducted in two steps. First, the aircraft was maneuvered with FAS in the failed mode at hover and at cruise airspeed to assure satisfactory handling characteristics in the failed mode. Next, FAS actuator hardovers were simulated at various airspeeds and maneuvers, as shown in Table I. The worst type of failure anticipated was an aft actuator hardover during a high speed, high g turn, since only a small aft stick movement would be required to increase the control loads. Therefore, the sequence of hardover testing was to start at the lowest airspeed shown in Table I and then proceed to the next higher speed.

Developmental testing established the program of FAS gains as a function of airspeed. These gains were based on subjective opinion of the two Sikorsky S-67 project pilots. The intent was to develop the best compromise over the whole range of maneuvers required of a high performance helicopter. The maneuvers of Table I were used to develop the FAS gain function in the following manner:

1. Constant speed, constant load factor turns were performed to calibrate the force gradient. Altitude was usually sacrificed to hold speed. Steady load factors varied from 1.5 g to 2.8 g.

2. Constant altitude, constant bank angle turns were performed to observe the variation in force gradient as a function of airspeed. Airspeed usually bled off rapidly, depending on the load factors.

3. 2 g symmetrical pullups followed by 0 g pushovers were also performed to calibrate the force gradient.

4. Constant speed "S" turns with rolling rates varying from 20 to 60 degrees per second were used to investigate control harmony.

5. The gun run maneuver started in cruise flight at approximately 150 knots. The objective was to perform a 180-degree course

TABLE I. FLIGHT TEST CONDITIONS

Flight Condition or Maneuver*	Airspeed (kn)	FAS Characteristics to be Evaluated
Hover, 100-ft altitude	0	1. FAS hardover failures 2. Control harmony 3. Stability and maneuverability
Takeoff and transition	0-80	1. Buildup of control force gradient
Level flight	100, 140, 170	1. FAS hardover failures 2. Stick-free stability and trim characteristics
Constant altitude turns Constant speed turns Rolling reversals "S" turns	100, 120, 140, 170	1. FAS hardover failures 2. Control harmony 3. Correlation of control forces and load factor during change of airspeed or altitude 4. Stick-free stability after stick release in high g flight 5. Ability to control rotor loading with collective stick shaker cue
Symmetrical pull-up and pushover	100, 120, 140, 160	1. Correlation of control force and load factor 2. Ability to control rotor loading with collective stick shaker cue
Quick stop from cruise flight to hover at cruise altitude	140, 170	1. Control force level required, and fade-out of force gradient below 80 kn

TABLE I - Continued

Flight Condition or Maneuver*	Airspeed (kn)	FAS Characteristics to be Evaluated
Split "S" Entry to landing pattern Simulated gun run		1. General compatibility of FAS with S-67 handling qualities

* Maneuvers were normally executed at 2000 to 3000 foot altitude. Altitude was varied during maneuvers as required.

reversal to a steady dive on target as quickly as possible. Usually, a sharp pullup with a wingover was performed at approximately 100 knots. A 25-30-degree nose-down run on target commenced with dive brakes deployed to minimize acceleration. After accelerating to 180-200 knots, dive brakes were retracted and a 2 g pullup was performed. The gun run maneuver involved high load factors, large attitude and stick excursions, and rapid changes in airspeed.

The Government FAS evaluation was conducted by three test pilots, representing USAAMRDL (Eustis Directorate), USAAMRDL (Langley Directorate), and NASA (Langley), who flew identical flight test plans with and without FAS. Each 1/2-hour test plan consisted of orientation to the S-67, takeoff, a series of turns and pullups followed by pushovers at various airspeeds, the gun run, landing approach, landing, hover, and 10 minutes for freestyle. Individual debriefing sessions after each flight, as well as group debriefings, were held to obtain a qualitative evaluation of FAS.

DESCRIPTION OF AIRCRAFT

The S-67 demonstrator aircraft is a high-speed derivative of the Sikorsky S-61 (SH-3D) helicopter. The aircraft is shown in three-quarter left view in Figure 1. The narrow, low-drag airframe was designed to meet the high-speed requirements of an attack mission. The cockpit is arranged in tandem with the copilot-gunner in the forward seat and the pilot in the aft, elevated seat. The pilot has downward visibility to -15 degrees over the nose. Two T58-GE-5 engines are mounted in the main rotor pylon above the fuselage center section.

The main rotor hub, tail rotor, drive system, and transmission systems are all SH-3D dynamic components. The main rotor has five S-61F blades, each with a twist of -4 degrees. The 22-inch blade tips are swept back 20 degrees to delay tip Mach number effects. The rotor control system uses SH-3D components.

The fixed-wing type control surfaces include the stabilator, a vertical stabilizer, and sponsons with stub wings. The vertical stabilizer is fixed. The tail wheel is attached to the base of the ventral fin, and the retractable main landing gear is housed in the wing sponsons. Wings are attached to the sponsons for additional lift and to provide attachment points for armament. The wing panels have speed brakes to control dive angle and increase deceleration capability.

Principal dimensions and general data for the S-67 aircraft are as follows:

Main Rotor

Diameter	62 ft
Normal Tip Speed (104 percent N_R)	686 ft/sec
Disc Area	3019 ft^2
Solidity	0.0781
Number of Blades	5
Blade Chord	1.52 ft
Blade Twist	-4 deg
Airfoil Section	NACA 0012 MOD
Articulation	full flapping and lagging
Tip Sweep	20 deg

Figure 1. S-67 Aircraft.

Tail Rotor

Diameter	10 ft 7 in. *
Tip Speed	700 ft/sec
Disc Area	83.9 ft^2
Solidity	0.1885
Number of Blades	5
Blade Chord	0.612 ft
Blade Twist	0 deg
Airfoil Section	NACA 0012 MOD
Pitch Flap Coupling	45 deg

Fuselage

Overall Length	64 ft 1 in.
Overall Height	16 ft 3 in.
Overall Width	27 ft 4 in.
Wheel Tread	7 ft
Wheel Base	36 ft 2 in.

Stabilator

Root Chord	4 ft 2 in.
Tip Chord	2 ft
Taper Ratio	0.48
Area	50 ft^2
Span	15 ft 6 in.
Aspect Ratio	4.8
Airfoil (Root)	NACA 0015
Airfoil (Tip)	NACA 0012

* Diameter was increased from 10 ft 4 in. prior to the FAS program.

Vertical Fin

Root Chord	7 ft 6 in.
Tip Chord (Upper)	2 ft 10 in.
Tip Chord (Lower)	3 ft 9 in.
Taper Ratio (Upper)	0.62
Taper Ratio (Lower)	0.5
Total Area	68.7 ft^2
Aspect Ratio	2.65
Airfoil Section	NACA 4415

Wing

Root Chord	4 ft 6 in.
Tip Chord	1 ft 11.5 in.
Overall Span	27 ft 4 in.
Total Exposed Area	58 ft^2
Incidence	8 deg
Dihedral	10 deg
Quarter Chord Sweep	10 deg 45 min
Taper Ratio (Exposed)	0.44
Aspect Ratio	8.0
Airfoil Section	NACA 4412

Propulsion System

Engines	Two T58-GE-5
Takeoff Power (each)	1500 hp
Military Power (each)	1400 hp
Normal Power (each)	1250 hp
Transmission Rating	2800 hp

Loading Conditions

* Empty Weight	10,900 lb
Maximum Gross Weight Flown	18,000 lb
Maximum Gross Weight Capability	21,800 lb
Center-of-Gravity Range	258 in. to 276 in.

* Aircraft less fuel, payload and crew.

DESCRIPTION OF FAS

The FAS is composed of three channels: pitch, roll, and collective. In addition, the system has a fault-detection capability to assure system shutdown if malfunctions that could cause undesirable control inputs occur.

THE PITCH CHANNEL

Figure 2 shows a block diagram of the pitch channel FAS. FAS is based on the measurement of aircraft load factor due only to aircraft pitch rates. In coordinated flight, load factor is the normal acceleration resulting from curvature of the aircraft flight path about a point in space. This normal acceleration (n_z) is the product of aircraft tangential velocity (airspeed, V) and aircraft rate of rotation (body pitch rate, $\dot{\theta}_f$), or

$$n_z = (V)\ (\dot{\theta}_f).$$

The variables V and $\dot{\theta}_f$ are measured by an electronic airspeed transducer and a rate gyro. The multiplication, $(V)\ (\dot{\theta}_f)$, is accomplished by an electromechanical servo device (servo-multiplier) that makes the gain on pitch rate ($K_{\dot{\theta}_f}$) a function of airspeed (V). The result is a signal proportional to the load factor due to aircraft pitch rates.

Two additional signals form a part of the FAS force exerted on the pilot's hand through the pitch control. One is a spring force generated by a signal proportional to the difference between the stick trim position (B_T) and the actual stick position (B_{1_s}). No breakout is associated with this electrical spring, except during taxi. The spring constant ($K_{\Delta B_{1_s}}$) is programmed to change with airspeed. This signal provides a trim capability and improves stick-free stability (force stability). The other FAS signal is a damper force proportional to the rate of pitch control stick displacement. The damper gain ($K_{\dot{B}_{1_s}}$) is also programmed with airspeed. Protection from abrupt control inputs, improved stick-free stability, and a control feel that precedes the actual maneuver are the principal goals of the stick rate signal. In addition, the rate signal helps provide mild shutdown characteristics by causing the operative actuator to move in a direction opposite that of the hardover actuator, as the stick begins to move before shutdown. The manner in which the three FAS signals are programmed as a function of airspeed determines the pitch control feel that the pilot experiences during maneuvers.

An amplifier sums the three FAS signals and applies an electrical current to a hydraulic servo valve whose differential pressure output is proportional to the current. The pressure difference acts across a piston to create the FAS force that the pilot feels during maneuvers. This force is exerted on the pitch control rod at the input side of the auxiliary servo.

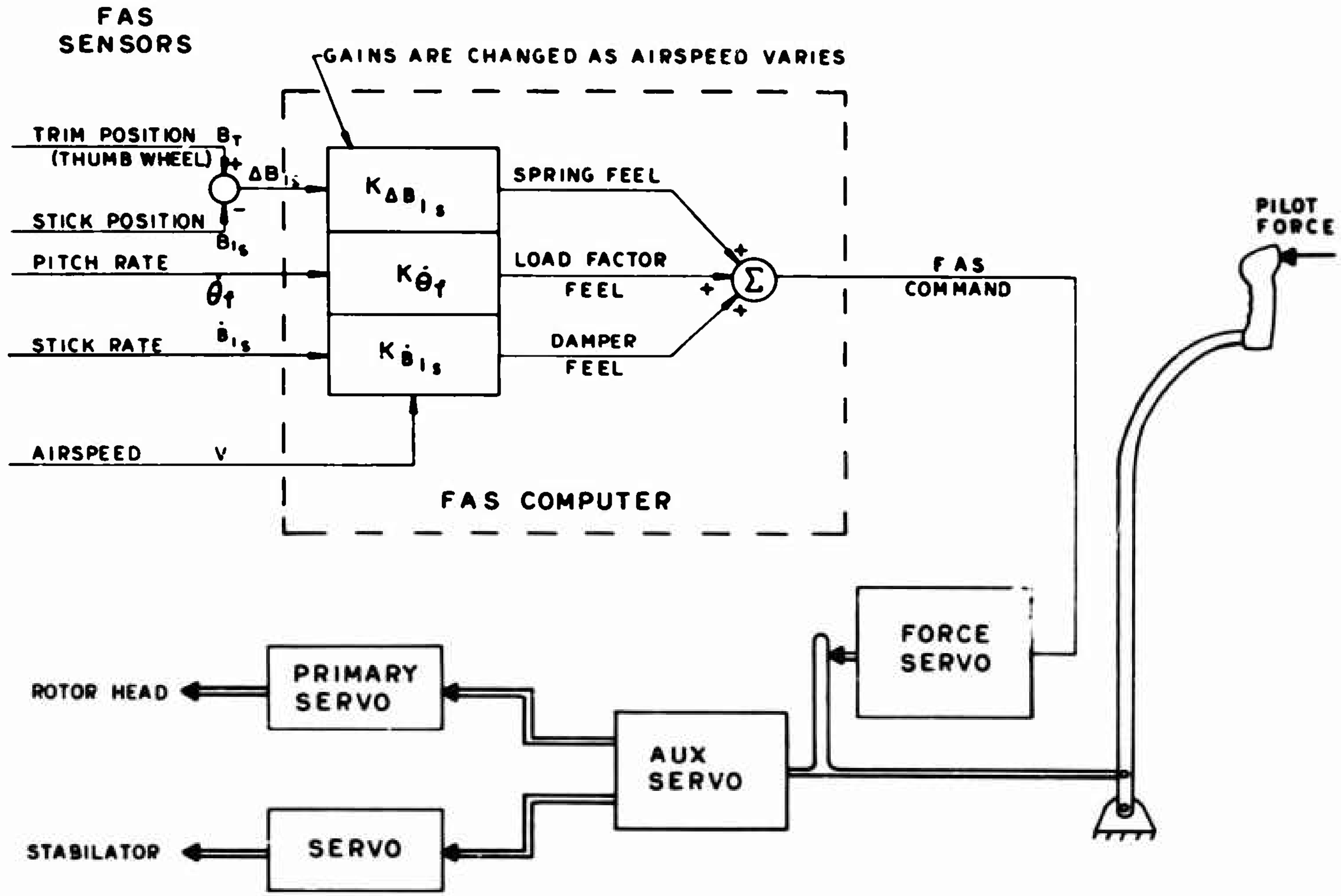

Figure 2. Pitch FAS.

Figure 3. FAS Cyclic Grip.

An integral part of the pitch FAS is the control stick trim system. The desired pitch trim position is commanded by the position of a trim wheel mounted on the side of the cyclic grip, as shown in Figure 3. Forces due to an out-of-trim condition can be trimmed away at any rate by the pilot. The system is capable of establishing any stick trim reference position with an accuracy of ±0.25 percent of full travel.

There is complete redundancy of the pitch FAS channel to provide a fault detection mechanism. This mechanism is explained in the section entitled FAS FAULT PROTECTION.

THE ROLL CHANNEL

Roll control feel augmentation is intended to complement the pitch control feel by providing control harmony. An earlier flight test program, conducted on a U. S. Marine CH-53D, determined that good control harmony could be achieved without using the electrohydraulic system required for the pitch channel. Satisfactory roll feel augmentation was achieved with passive mechanical components that exert two force components: one, a spring force proportional to control displacement from trim; the second, a damper force proportional to the rate of control displacement. These two force components do not require scheduling with forward airspeed.

The S-67 roll FAS, therefore, was implemented with passive mechanical components. Figure 4 shows how the present S-67 Automatic Flight Control System (AFCS) trim system was modified for this program to provide the spring force, damper force, and position trim. In the conventional S-67 AFCS, a hydraulic trim actuator and stick trim amplifier form a servo loop which controls the stick trim position. A trim release switch or a 4-way coolie hat button on the cyclic stick are used to change the trim position. The trim actuator is connected to the control linkage through a force gradient spring. For Roll FAS, the breakout force level of this spring was lowered to provide a smooth spring force. A parallel hydraulic damper was added to provide the damper force. The roll stick trim reference position was supplied from a trim thumbwheel mounted on top of the cyclic grip, as shown in Figure 3. The AFCS trim release switch and coolie hat button were no longer needed and were removed from the cyclic grip. These modifications yielded a roll control feel that depended only on the motion and displacement of the control stick, not on any subsequent aircraft response.

The S-67 roll AFCS was also used to provide roll quickening, which improves the correlation between pilot force input and aircraft roll response. This modification added a brief signal to the pilot's input every time he moved

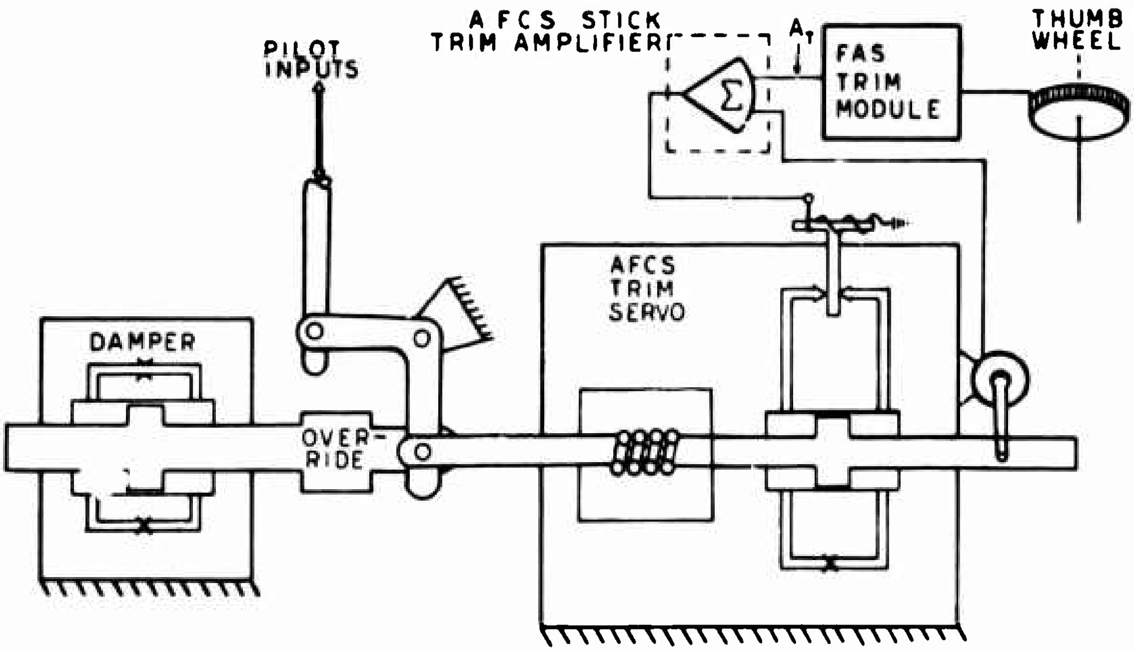

Figure 4. Roll FAS.

the stick in roll, thus quickening the initial roll response. This signal is fed forward from the pilot's stick to the auxiliary servo. The steady-state roll rate per inch of stick is unchanged, since the signal returns to zero when the stick stops moving. The pilot is able to achieve a crisp roll response with smooth stick motions when roll quickening is used. These smoother inputs are reflected in smoother control forces. Without roll quickening, momentarily larger and more abrupt pilot inputs would be required to achieve the desired roll response. The associated control forces would also be larger and more abrupt. Thus, roll quickening improves control feel, although roll quickening is not specifically a part of FAS.

THE COLLECTIVE CHANNEL

In the S-67, loads on the primary control components are sensed by a transducer attached to the right lateral stationary star. This transducer supplies the input to an amplifier which drives a meter known as the cruise guide indicator located on the pilot's and the gunner's control panel. During maneuvers, the pilot monitors the cruise guide indicator to detect increasing control loads. Proper management of the collective stick is essential to maintain control loads at the normal level. During a maneuver in a winged helicopter, the wing shares the g load with the rotor. If the rotor carries too much of the load, the rotor control system is subjected to increased loads. The pilot can reduce rotor control loads by lowering the collective stick. This action transfers the g load from rotor to wing, but also reduces forward thrust. Too large a reduction in collective, therefore, is undesirable. To maintain the control loads within the normal range, the pilot moves the collective stick to keep the cruise guide indicator reading as high as possible during maneuvers, but below the normal control load limit. Since control loads are sensitive to small collective or cyclic pitch control movements, considerable attention to the indicator is required. This procedure diverts the pilot's attention from the "outside world" to the cruise guide indicator and can degrade performance in maneuvers.

In the S-67 equipped with FAS, a collective stick shaker exerts a vibratory force cue on the collective stick. It provides the pilot with a feel for rotor control loads without requiring attention to the cruise guide indicator. A functional block diagram of the device is shown in Figure 5. The stick shaker is a constant frequency device that varies the amptitude of vibration in response to control loads. The frequency of vibration is approximately 25 cps in the plane that is perpendicular to collective inputs, so that the vibrations are not transmitted to the control system. The shaping network can be adjusted to initiate stick vibration at the desired rotor control load level and also to increase the vibration amplitude with increasing control load.

With the collective stick shaker, the pilot enters a maneuver without having to watch the cruise guide indicator. If control loads increase above the normal operating level, the stick begins to vibrate. This operating level is not the rotor control load limit, but is a well defined value above which further collective or cyclic control inputs would cause the control loads to increase rapidly. When the stick begins to shake, the pilot, to make cyclic control inputs, should reduce the collective setting so as to maintain the control load near the operating level. Also, the intensity of vibration indicates the amount by which the control load has exceeded the normal operating load level.

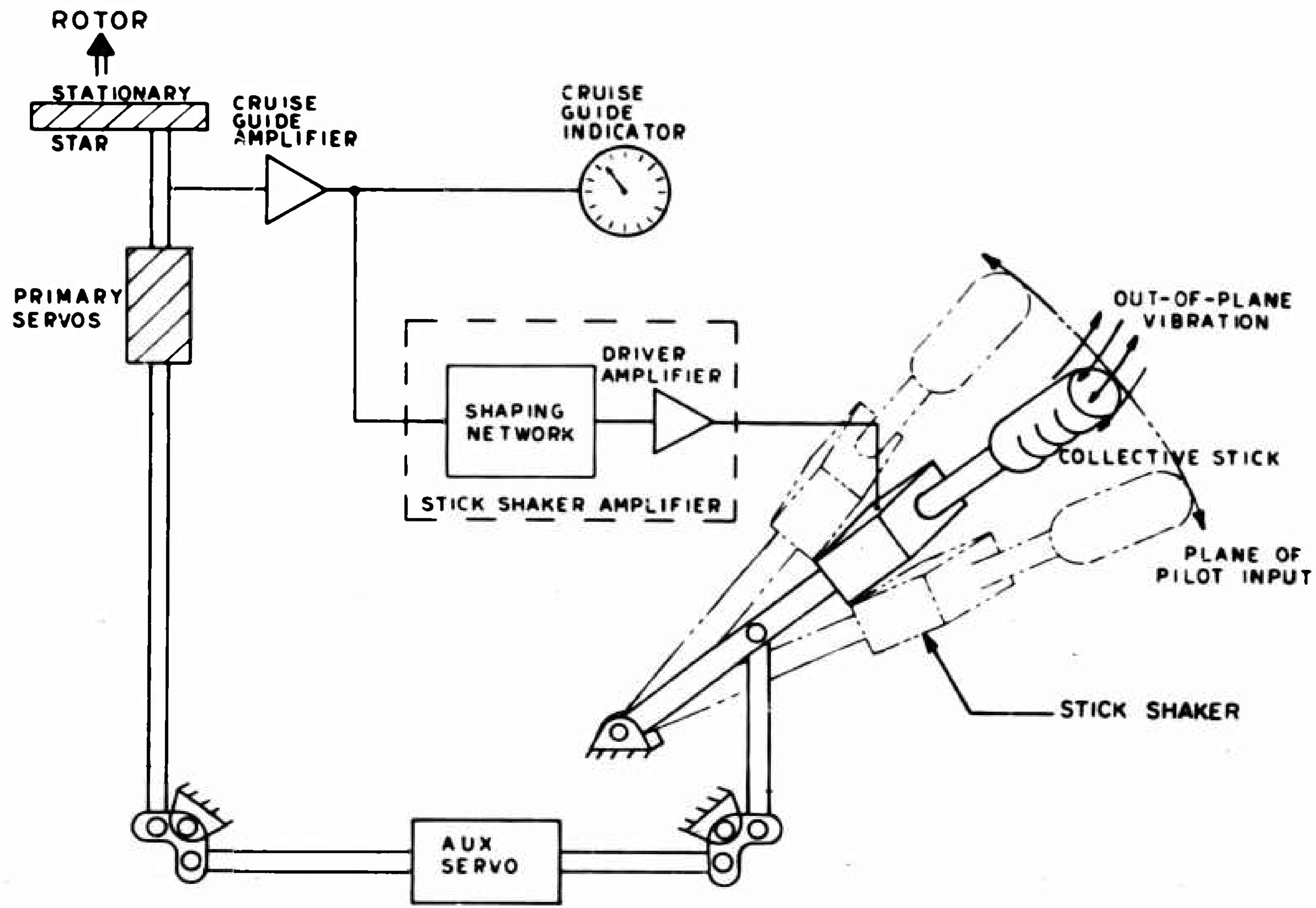

Figure 5. Collective FAS.

FAS FAULT PROTECTION

A necessary design consideration for the S-67 FAS was the consequence of possible system failure, since the pitch channel FAS is, in effect, a powerful flight control system with ten times the authority of the AFCS.

Fault detection was designed into the pitch channel of the FAS to detect any component failure that would cause either a large or a rapid stick displacement. The design goal for stick motion following a FAS malfunction specified that stick displacement must be less than 10 percent unless the rate of stick motion was less than 10 percent per second.

The pitch FAS consists of dual sensors, computers, and actuators, as shown in Figure 6. The output forces of the twin FAS actuators are compared by a mechanical yoke for fault detection, as shown in Figure 7. The yoke transmits the sum of the FAS forces to the control rod as control feel, but a force mismatch between the twin actuators exceeding the detent mechanism level will cause the yoke to tilt, triggering the shutdown mechanism. The detent mechanism level is 20 pounds at the yoke, or 5 percent of the maximum force capability of the actuator. Yoke tilt angle is monitored by dual synchros, and fault detection occurs when the yoke angle exceeds a 3-degree level. Transition from the normal operating mode to the shutdown mode occurs rapidly and before the stick can move far or the pilot can react. After a FAS shutdown, the FAS actuator becomes a passive hydraulic damper. This feature enables a smooth change in stick feel during transition from FAS "on" to FAS "off". If one of the FAS actuators should jam, the FAS yoke would pivot about the jammed actuator, allowing 50 percent stick travel. The FAS override spring compresses when the pilot applies a force of 40 pounds, allowing 100 percent stick travel. The roll channel FAS uses the existing AFCS trim servo valve, which is made safe by a rate limitation. The added hydraulic damper is a passive device, so fault detection is not required. Protection from a jammed damper is provided by an override spring capsule with a force of 15 pounds (see Figure 7).

Since the collective stick shaker vibrations are not transmitted to the helicopter control system, control inputs cannot result from failure of the collective FAS. A complete discussion of possible FAS failures is contained in the Appendix.

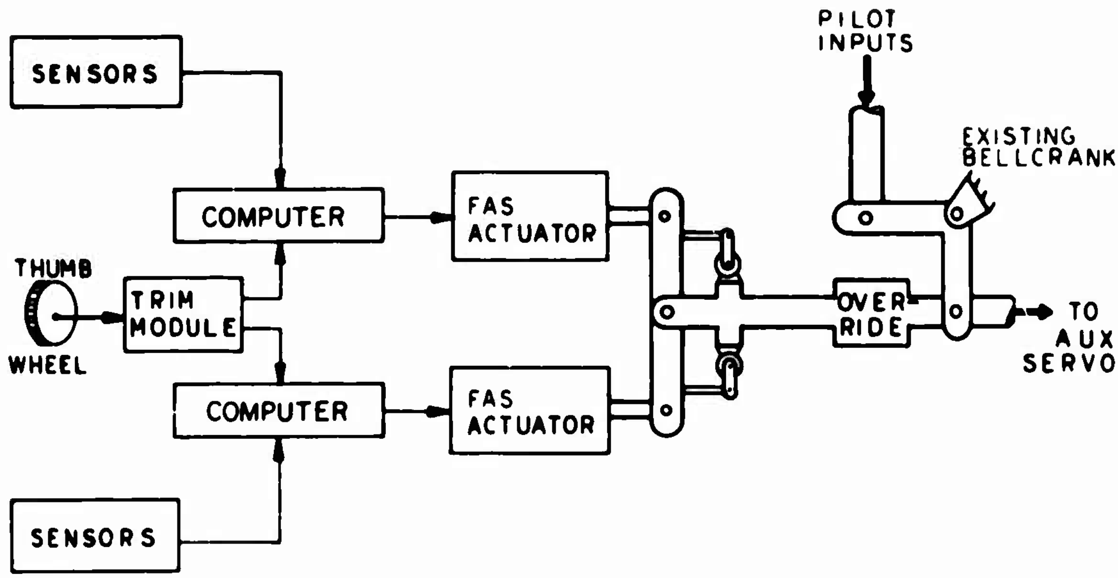

Figure 6. Pitch FAS Redundancy.

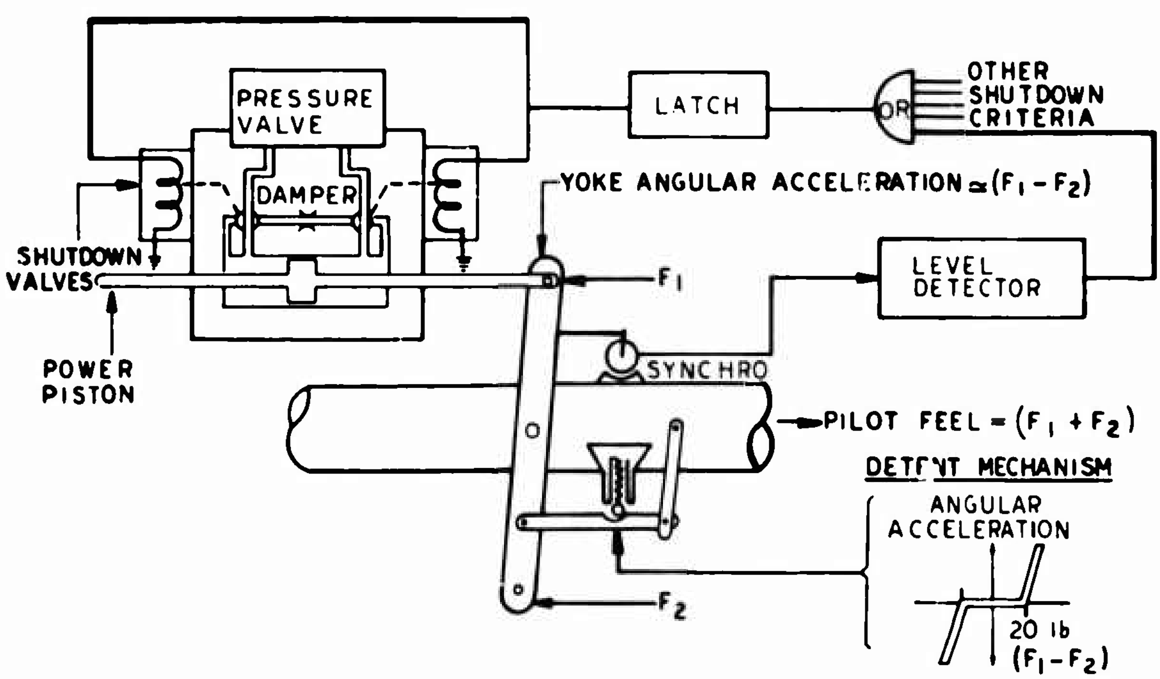

Figure 7. Fault Detection and Shutdown System.

FLIGHT TEST RESULTS

The flight tests were conducted from August 17, 1971 to September 1, 1971. The results presented are considered representative for the maneuvers listed in Table I.

DEVELOPMENT TESTING

The objective of the development testing was to determine the configuration of the pitch, roll, and collective FAS channels that would simultaneously provide load factor feel, control harmony, and rotor control load feel.

Pitch Channel

The maneuvers of Table I used to evaluate the correlation of control forces and load factor were executed repeatedly at each airspeed. During these maneuvers the three FAS pitch gains of fuselage pitch rate ($K_{\dot{\theta}_f}$), spring ($K_{\Delta B_{1_s}}$) and damper ($K_{\dot{B}_{1_s}}$) were adjusted. The gains were first set during steady maneuvers to achieve a constant force per g of load factor as well as stick-free stability. Steady maneuvers, used for determining the stick force per g, are defined as those where the pitch cyclic stick position and aircraft load factor are constant for 2 seconds or more. Then based on the pilot's subjective opinions, further adjustments were made to improve the control feel and harmony during transient maneuvers such as rolling reversals and "S" turns.

On completion of the gain setting phase of testing, a set of pitch FAS gains was determined for the test condition airspeeds of Table I. These gains were then averaged to give the gain vs. airspeed plots as shown in Figure 8 that could be programmed automatically by an electromechanical servo-multiplier.

Figure 9 shows a typical 140-knot high load factor turn. In this figure, the pitch stick force leads the load factor buildup (due to stick rate) and then follows the load factor despite changes in collective and cyclic stick settings. The following example shows how the stick force per g results from the three pitch FAS gains of Figure 8.

Example

At any airspeed, the total longitudinal force applied to the cyclic stick can be expressed as

$$\text{stick force} = (K_{\dot{\theta}_f})(\dot{\theta}_f) + (K_{\Delta B_{1_s}})(\Delta B_{1_s}) + (K_{\dot{B}_{1_s}})(\dot{B}_{1_s})$$

In Figure 9, the peak load factor occurred 11.0 seconds from the start of the maneuver. At this time, the cyclic stick had been moved aft of the trim point by 14 percent, so $\Delta B_{1_s} = 1.96$ inches. The stick was not moving so $\dot{B}_{1_s} = 0.0$ inches per second, and the pitch rate was $\dot{\theta}_f =$ 16.5 degrees per second. Figure 8 shows the following values of the FAS gains at 140 knots:

$K_{\dot{\theta}_f} = .75$ pounds per degree per second

$K_{\Delta B_{1_s}} = 4.75$ pounds per inch

$K_{\dot{B}_{1_s}} = 2.0$ pounds per inch per second.

Substitution of these gains and data into the above stick force equation gives

stick force = (.75) (16.5) + (4.75) (1.96) + (2.0) (0.0) pounds.

stick force = 21.7 pounds.

From Figure 9, the measured stick force was 25 pounds and the load factor was 2.45g. The error in the computed stick force can be attributed to calibration errors. Using the measured values,

$$\text{stick force per g} = \frac{\text{stick force}}{\text{load factor} - 1.0g}$$

stick force per g = 17.2 pounds per g.

Figure 10 shows a symmetrical pullup and pushover in which the stick force leads the load factor. Short-term variations in stick force resulted from variations in the stick rate signal. A peak load factor of 2.0g occurs 3.50 seconds from the start of the maneuver. The stick force due to stick movement and the stick force due to pitch rate can be computed as in the example to be 6.7 pounds and 6.0 pounds respectively, or a total of 12.7 pounds. The measured stick force is 16.0 pounds and the resulting stick force per g is 16.0 pounds per g.

The relationship of stick force and aircraft load factor during typical steady maneuvers is shown in Figure 11. The result used in the example is point A. The slope of the line shows the force gradient to be 18 to 25 pounds per g for airspeeds above 100 knots.

The flight data of Figure 12 shows the stick force per g as a function of airspeed. Again, the result of the example is point A. The force gradient exhibited a smooth reduction to zero as airspeed decreased below 80 knots.

The increase in force gradient from 18 pounds per g at 100 knots to 25 pounds per g at 170 knots was to inhibit control inputs at the higher airspeeds.

As the pilot moved the stick to start a maneuver, the FAS damping force increased due to the rate of motion of the stick before the aircraft load factor increased. Thus, the increased control forces correlated with the pilot's entry into the maneuver. The stick rate forces subsided as the stick rate decreased, but the stick deflection and pitch rate forces increased so that a smooth, continuous force buildup resulted.

The flight maneuvers shown in Figures 13 and 14 are also pertinent to the evaluation of FAS on the S-67. Figure 13 shows that, without endangering aircraft safety, the cyclic stick can be released while holding a 25-pound force. Even though the aircraft pitch attitude changed from 15 degrees to 35 degrees nose down in about 3 seconds, the pilot was easily able to recover from the condition. Figure 14 shows that aircraft and stick were well damped over the short term, and that no loss in stick-free stability resulted from the FAS pitch rate gain function.

Stick force feel in the pitch channel in hover was only stick rate and friction forces. The electrical damping rate of 0.75 pound per inch per second of stick motion combined with the actuator inherent damping to give a total of 1.50 pounds per inch per second.

Stick centering was provided during taxiing to keep the stick from falling when the pilot removed his hands to perform other tasks. The stick trim system was engaged automatically by a landing gear scissors switch when the landing gear was depressed. The stick centering force had a breakout of 6.0 pounds centered about the stick trim position.

Pitch stick trim sensitivity was such that six full rotations of the thumbwheel would give full stick travel. One-third of a thumbwheel rotation could be achieved with one thumbing motion. When trimming away forces with the stick fixed, the force change per thumbing motion varied, since the gain of force as a function of stick deflection changed with airspeed (see Figure 8). At 140 knots, one full thumbing motion caused approximately a 4-pound change in stick force.

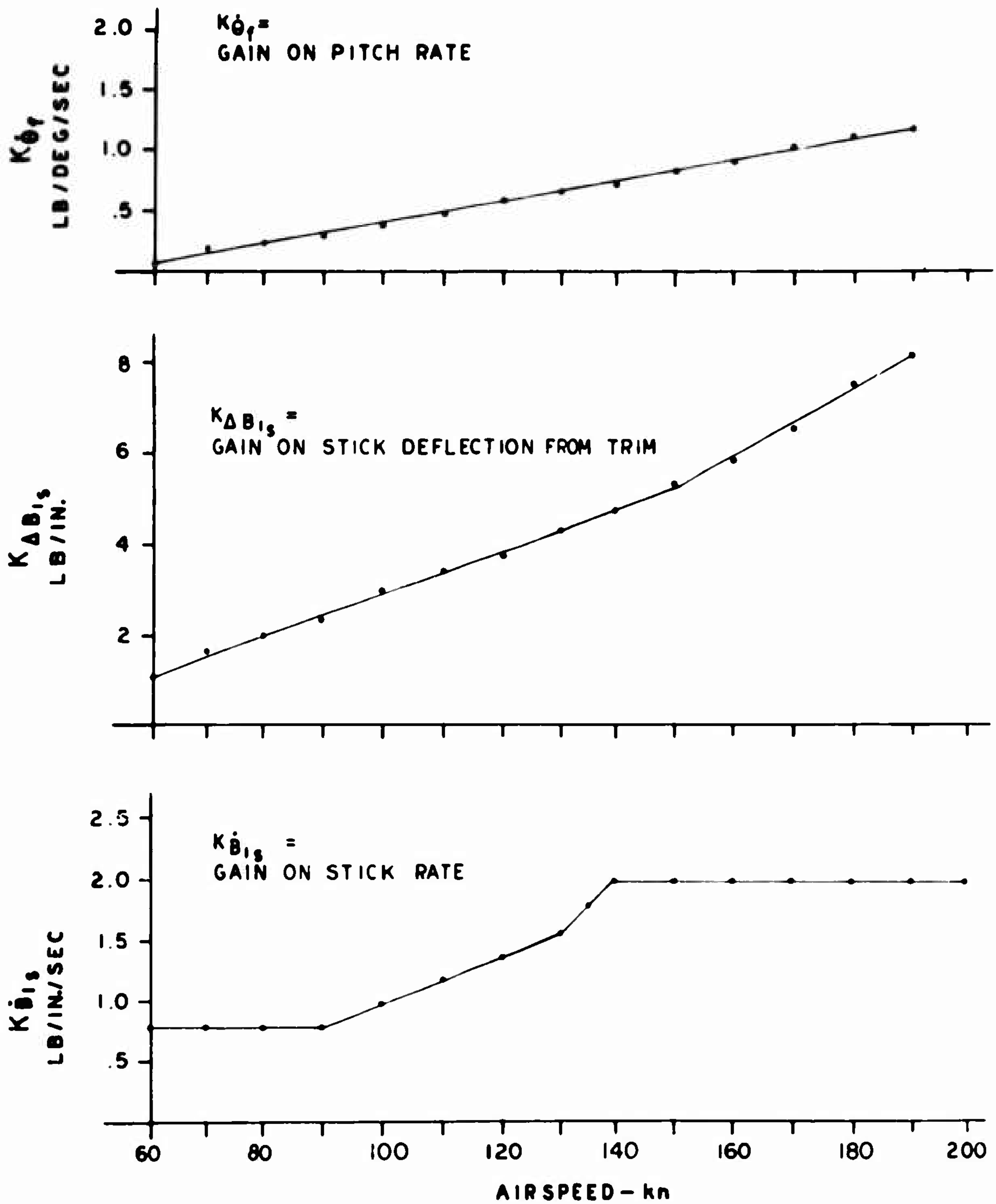

Figure 8. Pitch FAS Gain Program.

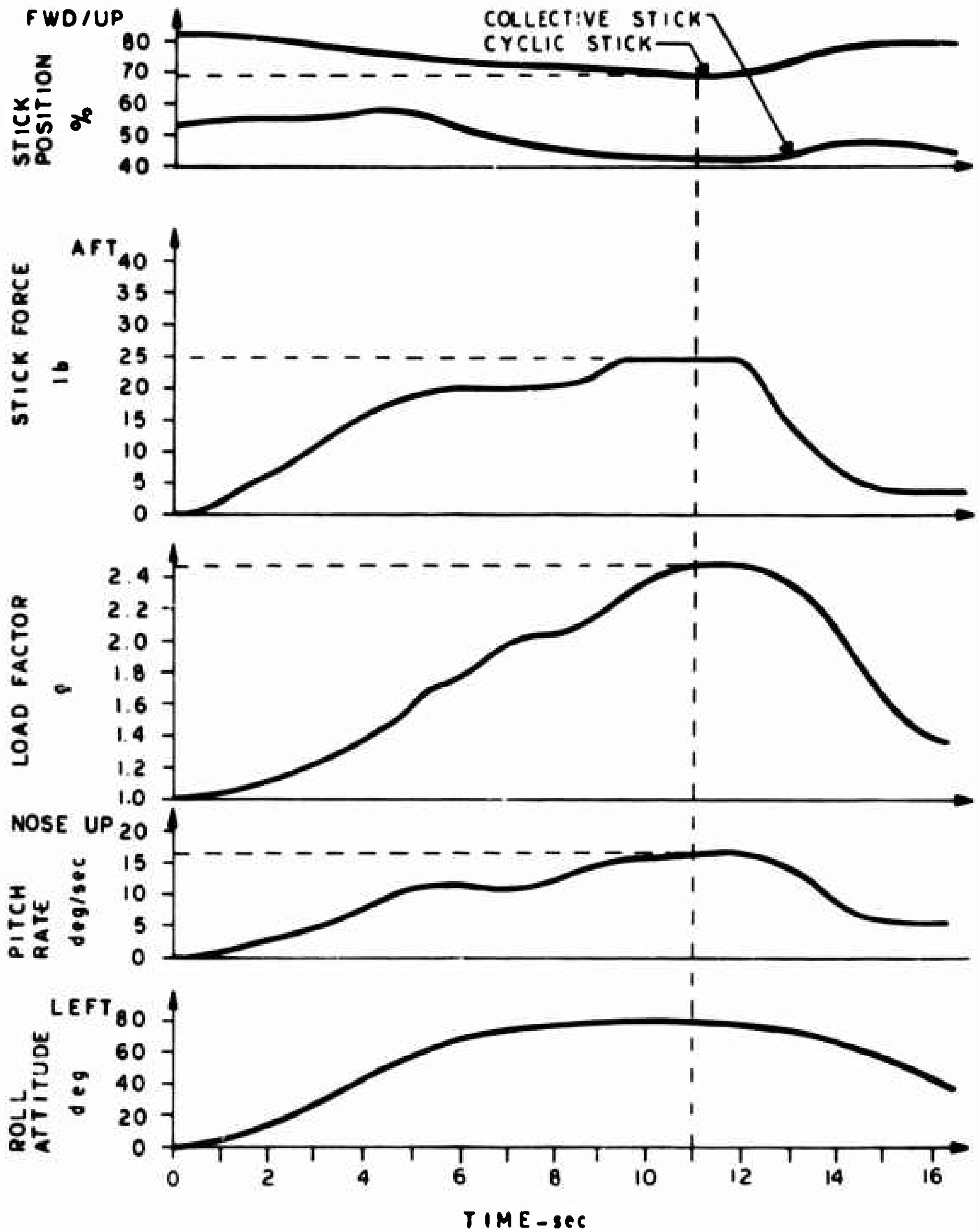

Figure 9. High Load Factor Turn at 140 Knots With FAS.

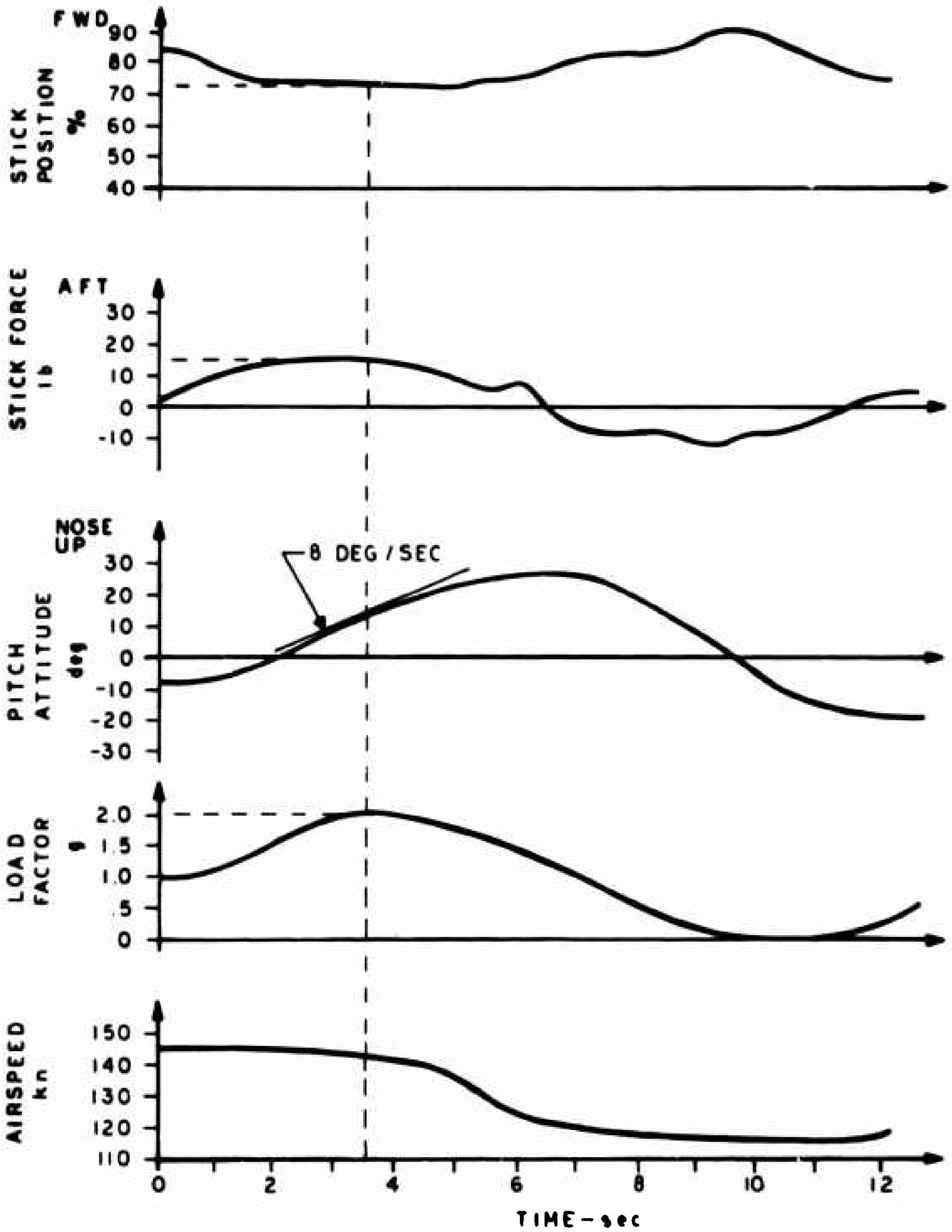

Figure 10. Symmetrical Pullup and Pushover With FAS.

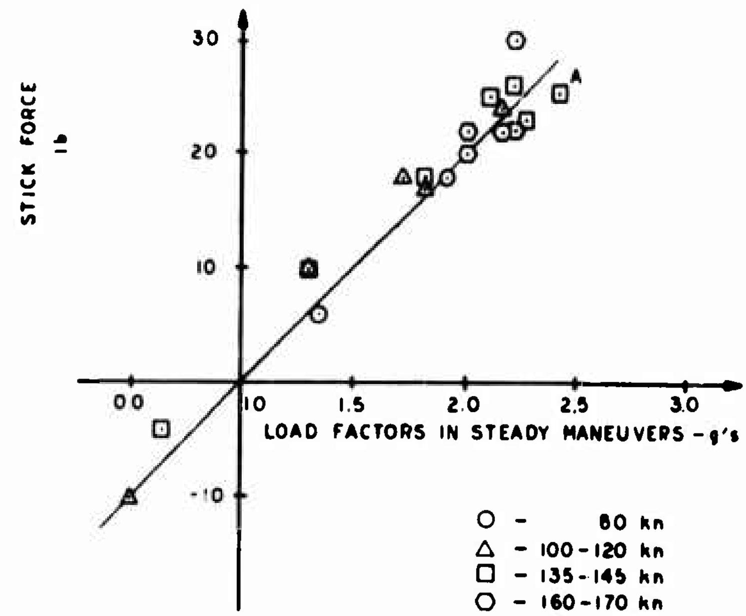

Figure 11. Pitch Control Forces During Constant Load Factor Maneuvers.

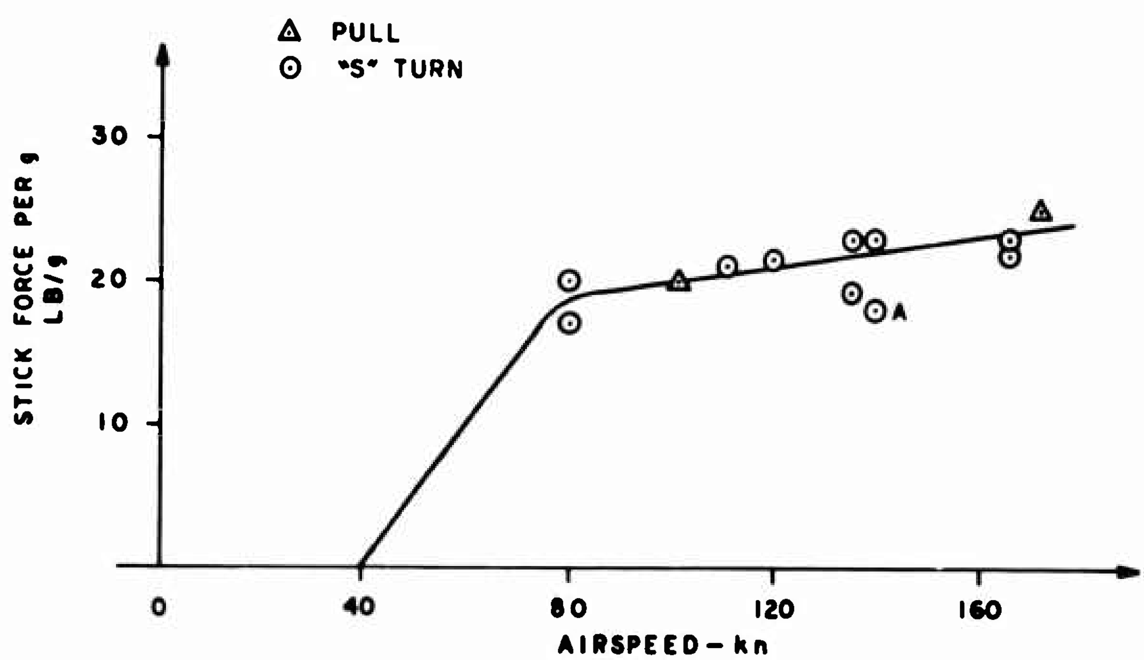

Figure 12. FAS Force Gradient in Steady Maneuvers.

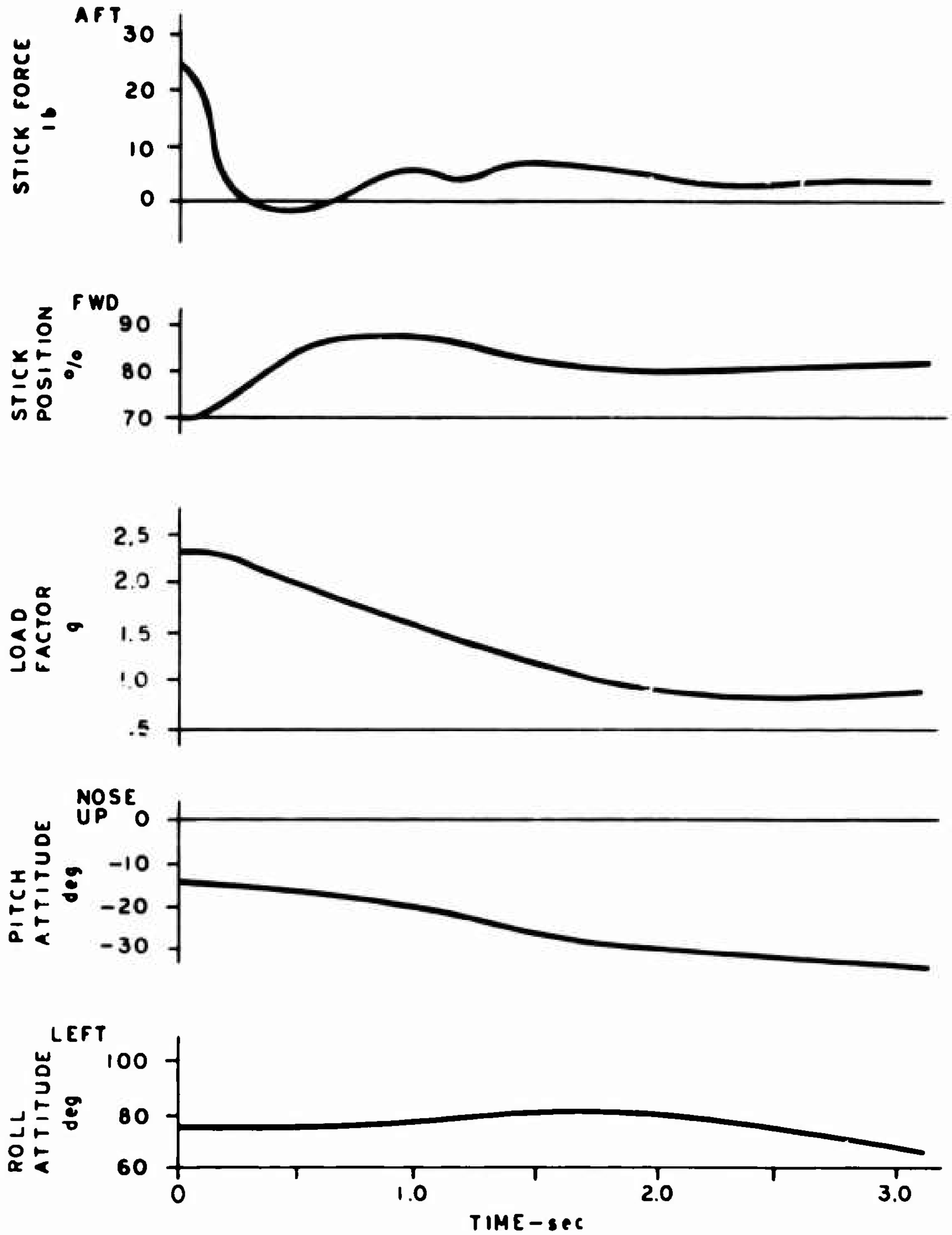

Figure 13. Stick Release During a High g Turn With FAS.

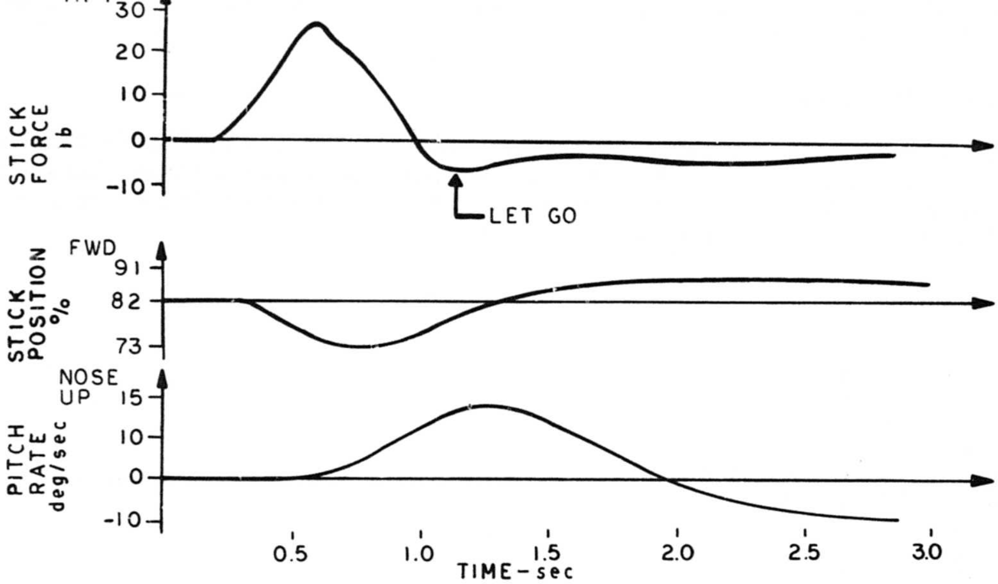

Figure 14. Stick Pulse Input During Level Cruise Flight With FAS.

Roll Channel

After initially setting the pitch gains, the control harmony was evaluated by executing rolling reversals and "S" turns. These maneuvers, executed at the airspeeds of Table I, resulted in high roll rates and large roll stick motions.

The design values of the three roll stick forces, the damper force, the spring force, and the breakout force, resulted in satisfactory control harmony at all airspeeds above 60 knots. The damper force, engaged at all times, was 2.0 pounds per inch per second. The spring force was 0.5 pound per inch, and the total breakout force was 1.1 pounds. The breakout force has two components: a preloaded spring with a 0.75-pound detent centered about the stick trim position, and seal friction in the actuators.

In the presence of the spring and damper forces, the trim detent force was not noticeable when moving the stick through the trim point during maneuvers. The spring and trim detent breakout forces were engaged at airspeeds above 60 knots and also when the landing gear scissors switch was depressed. The damper force and actuator friction are the only roll stick forces in hover. The roll stick trim sensitivity was the same as the pitch, except that a 1.4-inch-per-second trim rate limitation was inherent in the trim actuator.

The roll quickening gain developed prior to installation of FAS did not require additional adjustment. Roll quickening gave an additional 5-percent short-term control input for a 10-percent stick motion. The washout time constant in removing the roll quickening input was 3.0 seconds. With FAS, roll quickening was engaged at all airspeeds and provided smooth and consistent roll feel.

Collective Channel

Flight testing of the collective shaker established the operating level at which the stick began to vibrate and the level at which maximum vibration occurred. The resulting amplitude of vibration as a function of cruise guide indicator reading is shown in Figure 15.

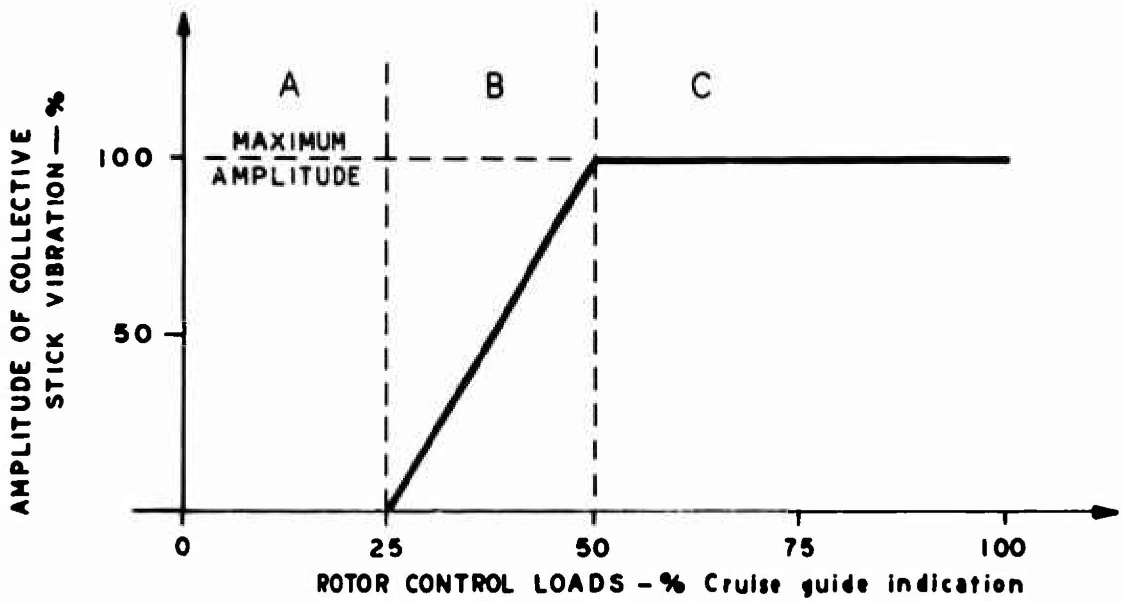

Figure 15. Collective Stick Vibrations.

The cruise guide indicator measures flight control loads at the primary servos. The S-67 is not normally operated with control loads above a cruise guide indicator of 60 percent. The results of previous flight testing [3] have shown that, during maneuvers, control loads build up rapidly when the cruise guide indication goes above 25 percent, while the increase in aircraft performance is not significant. Thus, the S-67 is flown in

[3] Montleone, Robert A., ANALYSIS AND FLIGHT TEST OF THE MANEUVERABILITY OF THE S-67 WINGED HELICOPTER, SER-67008 Sikorsky Aircraft, Contract DAAJ02-71-C-0008, USAAMRDL Technical Report (estimated publication date is October 1972), Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia.

maneuvering flight with a normal operating load level of 25 percent. For control loads below 25 percent (region A of Figure 15) there is no stick vibration. If the control loads rise above 25 percent, the stick begins to vibrate, indicating that control loads are about to increase rapidly. For cruise guide readings from 25 percent to 50 percent (region B of Figure 15) the amplitude of vibration increases with increasing loads. At 50 percent cruise guide reading, the amplitude of vibration reaches the maximum, and the amplitude remains constant for control loads above this level (region C of Figure 15). The frequency of vibration was constant at 25 cycles per second. A .27-second time lag on the signal to the stick shaker circuit was required to give a transient response in vibration amplitude that correlated with the cruise guide indicator reading.

SAFETY OF FLIGHT TESTING

FAS failures were simulated by applying a step input of current to the servo valve of one of the dual pitch channel actuators at the flight conditions presented in Table I. These hardover failures caused stick motions that were perceptible by the pilot, but that resulted in negligible aircraft response. In all cases, FAS failures were contained within the FAS failure design goal prescribed previously. Table II shows the results of the worst FAS failures in hands-on and hands-off cruise flight and during severe maneuvers. The flight test record for the worst of these cases is shown in Figure 16. It shows that the stick moved 0.3 inch at a rate of 33 percent per second. The fuselage pitching rate was only 1.0 degree per second, a negligible rate compared to the 10-degree-per-second rate allowed by Paragraph 3.5.9(a), MIL-H-8501A.

The FAS failures simulated during flight testing were even milder than the characteristics predicted by the actuator analog simulation which is presented in the Appendix. Figures 16 and 18 show that the values of stick force, yoke angle, and stick position are similar to the predicted values. The initial pulse in the stick force results as the hardover actuator accelerates to its maximum rate of 100 percent per second. Then the force subsides as the stick moves at constant velocity, causing yoke tilt and some stick motion. The magnitude of this initial pulse was 17 pounds at the servo or 1.22 pounds at the stick in the analog simulation, while in the flight test, the magnitude was 3.0 pounds at the stick. In both the analog simulation and the flight test, shutdown was initiated when the yoke angle reached 3.0 degrees. During the shutdown of the FAS actuators, which required 20 to 40 milliseconds, the stick decelerated and caused the reverse pulse in stick force. In the flight test, the stick was restrained from rapid motion after shutdown by the 2.0-pound-per-inch-per-second damper. However, the stick gradually returned forward due to its unbalanced weight.

Unexpected FAS shutdowns were experienced on five occasions during the flight test program. The FAS fault detection shut the system down with negligible aircraft response. In no instance did the aircraft stick responses exceed those shown in Table II. No failures were experienced in the roll and collective channels of FAS.

TABLE II. FLIGHT DATA SHOWING MAXIMUM STICK MOTION AFTER INTENTIONAL FAILURES

Type of Failure	Maneuver	Maximum Stick Rate (pct/sec)	Maximum Stick Displacement (pct)
100 percent aft hardover	Hands-on cruise	20	1.0
	Hands-off cruise	44	2.0
	2 g turn at 135 kn	24	3.5
	2 g turn at 165 kn	11	5.0
Stick release while holding 20-30-lb force	2.4 g left turn at 135 kn	33	9.0
	1.7 g left turn at 170 kn	25	6.0

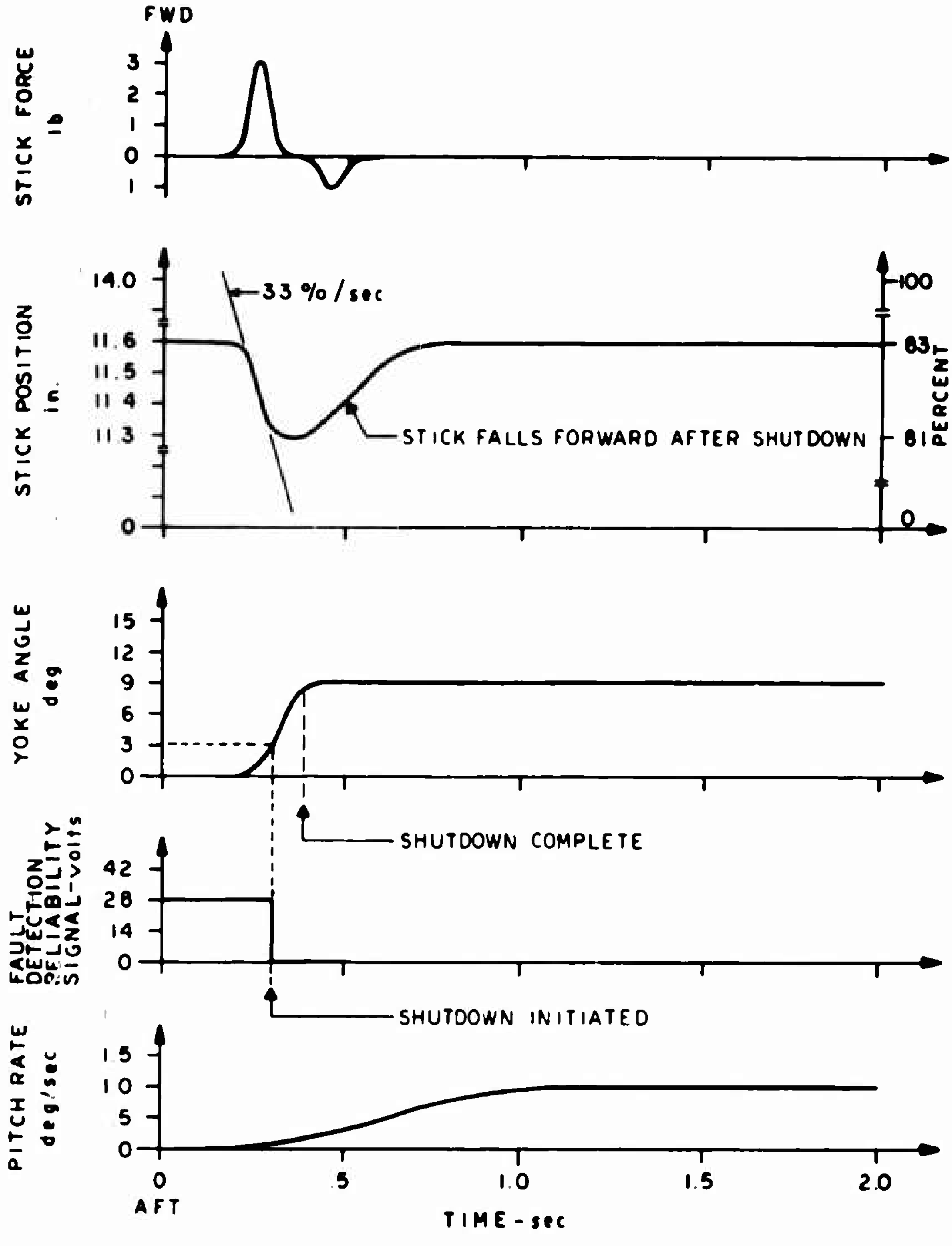

Figure 16. Intentional 100 Percent Hardover in One FAS Actuator During Hands-Off Cruise Flight at 140 Knots.

GOVERNMENT FLIGHT EVALUATION

FAS flight evaluations were conducted on August 31, 1971, and September 1, 1971, by three Government test pilots chosen by the Eustis Directorate. The flight test plan flown by each pilot was identical and each made two flights, one with FAS on, the other with FAS off. The total flight time for the six evaluation flights was 5-1/2 hours. Debriefings were conducted with each pilot immediately after each of the flights. Areas for improvement were indicated, and some problem areas were pointed out. The general opinion was that flight testing was too short to allow the pilots to become completely familiar with the basic handling qualities of the S-67. Flight test records obtained during these flights have previously been submitted to the Eustis Directorate technical representative along with voice recordings of the debriefing sessions. The following sections present the reports of the three evaluation pilots. (Note: These reports have not been edited in any way.)

Pilot Number 1: LTC Thomas C. West, Langley Directorate, USAAMRDL

1. The Sikorsky Feel Augmentation System (FAS) was flight tested during two flights in the S-67 Blackhawk on 31 August and 1 September 1971 at Sikorsky Aircraft, Stratford, Connecticut. In order to assess the relative value of the FAS system, this system was not engaged during the second flight. The flight test also addressed three other systems installed on the S-67; the roll quickener, the roll/pitch trim and the collective stick shaker although these systems were not the primary subject of the flight tests. The S-67 was flown primarily in maneuvering flight; constant altitude/load factor turns, symmetrical pullups, roll reversals, gun runs.

2. System Description. A brief description of the systems mentioned above is provided as a frame of reference upon which the pilot comments are made. No attempt was made to provide a detailed technical discussion of the functioning or mechanization of the systems as this is provided in other literature.

a. Feel Augmentation System - The Feel Augmentation System is essentially an adaptive control system engineered to provide the pilot with positive maneuvering stability in the high speed (90 to 200 kt) regime with a constant stick force per g gradient (approximately 15 lbs/G). This gradient reduces sharply below 80 kts to provide light stick forces normally associated with conventional helicopters. The system was designed to provide the pilot a more precise capability to maneuver in the high speed regime without fear of inadvertently exceeding the structural limitations of the aircraft and yet not degrade handling qualities through high stick forces in the low (below 80 kts) speed regime. Control harmony is achieved through a similar system in the roll axis. The system functions through a variable gain schedule of aircraft pitch rate, stick rate and stick deflection from trim as a function of airspeed.

b. Roll Quickener - The roll quickener increases the apparent roll sensitivity through shaping the roll response curve to provide a lower time constant. It does this by commanding a greater roll rate than requested and then washes out as desired rolling velocity is approached. The pilot sees this as a more responsive aircraft in roll.

c. Roll/Pitch Trim System - The roll/pitch trim system is a relatively novel system consisting of two trim wheels mounted on the cyclic stick, one for each axis (roll and pitch). Each wheel commands a trim position rather than a trim rate normally found on service aircraft (chinese coolie hat).

d. Collective Stick Shaker - The collective stick shaker is a novel if not unique system designed to provide the pilot with a cue to replace the aerodynamic vibratory cue lost as a result of advancements in rotor technology which would warn the pilot of impending blade stall in the high speed, high G environment. The system is mechanized through the cruise guide system which measures star load stresses and causes the collective stick to vibrate or shake laterally when high star loads are reached. The collective stick shaker was stricly experimental in nature and no attempt was made to optimize its functioning and response.

3. The Feel Augmentation System (FAS) provided the force feel intended through the flight envelope investigated. There were no apparent cross coupling effects attributable to the system noticed. The force gradient in the high 'q' regime was assessed to be too high in high G maneuvering flight but acceptable during low G maneuvers (below 1.5G) in the same regime. Excessive pilot attention to longitudinal stick inputs was required to reach and sustain a specific G level relative to the 'no FAS' case. This assessment must be tempered with the pilot's personal preference for lower stick forces throughout the flight envelope. In spite of this personal preference, the value of high stick forces as limit load factor is approached is obvious and desirable. Satisfactory cyclic force control harmony was achieved with the roll quickener operational but was degraded significantly with the roll quickener off. Lateral forces were excessively high relative to the longitudinal requirement during roll reversals and gun runs. The force gradient was noticeably lighter during flight below 80 kts as expected and was acceptable. FAS system failures were performed and found totally controllable in all flight regimes. Pitch excursions following failure were most docile. System failures were manifest by a slight longitudinal stick jump of approximately 1/2 inch in the direction of failure followed by a slow pitch down regardless of direction of failure (fore and aft). The apparent inconsistency of pitching response with aft failures may have been the result of a longitudinal stick imbalance resulting from an excessive stick forward trim position in high speed flight. In a 2 G level turn, failures resulted in a tightening of the turn until arrested. Overall rating of the FAS system is determined to be 4 (Harper-Cooper) during normal operation and a rating of 2 for all modes of failure performed.

4. The roll quickener significantly enhanced the roll characteristics of the S-67. Desired roll rates were easily achieved and response following a lateral input was crisp and well damped. Roll response with roll quickener off was adequate but sluggish relative to the 'on' case. Additionally, as mentioned in paragraph 3, control harmony was degraded as a result of higher apparent lateral stick forces with roll quickener off. The roll quickener improves the roll characteristics of the S-67 by at least one rating relative to the 'off' case.

5. The roll/pitch trim system was found to be acceptable throughout the flight envelope and a definite step in the right direction relative to standard trim rate systems. The aircraft was able to be trimmed in pitch without excessive difficulty. However, the trim sensitivity in pitch was considered low in that excessive trim wheel motion was required to achieve zero force with significant stick movement from an initial trim condition. The roll trim was unsatisfactory in that desired roll trim was difficult to achieve due to a viscous lag which would cause the pilot to overshoot desired trim condition following initial movement of the wheel to a new trim position. The result was an iterative process of ever-decreasing motions around the trim point until the pilot finally decided the 'cure was worse than the sickness'. Ratings of 3 and 5 are assigned to the pitch and roll trim capability respectively.

6. The concept of the stick shaker and its function is not new to the aircraft industry but is unique in rotary wing aircraft. As vibratory loads decrease with improved rotor systems particularly those which are associated with impending blade stall and high stress levels some other mechanism or cue must be provided the pilot to warn him of these conditions. The stick shaker is just such a mechanism. The mechanization of the stick shaker on the collective stick is appropriate and natural in that it keys the pilot directly to the proper control to move to alleviate the situation. The stick shaker on the S-67 was effective as a qualitative cue of warning but having this information the pilot sought a quantification of this warning. Reference to the cruise guide was the obvious answer. This solution to the quantification problem would not be acceptable if heads up flight is stipulated. Although there was some change in vibration of the stick as the aircraft progressed farther into the warning area the change was inadequate to perform the quantification function. The concept of the stick shaker is a good one. The quantification is equally important because armed with this information, the pilot is able to more precisely and efficiently utilize the entire performance envelope without fear of overstressing the aircraft. Further research of the stick shaker or similar system is warranted and encouraged.

<u>Pilot Number 2:</u> Mr. Perry L. Deal, NASA - Langley

Two flights were made recently by this pilot in the Sikorsky S-67 Blackhawk helicopter at Sikorsky Aircraft, Stratford, Connecticut in conjunction with an Army program to access the relative benefits of the Feel Augmentation System (FAS) in high speed maneuvering flight. A description of the aircraft was given in a memorandum to the Director for Aeronautics, Acting, dated July 12, 1971, entitled "Pilot Comments on the

Sikorsky S-67 Blackhawk Helicopter." A description of the Feel Augmentation System is provided in the attached AHS paper entitled "Feel Augmentation and Sensitivity Control in High Speed Helicopters," by Sean J. O'Connor of Sikorsky Aircraft.

The first flight was made with the FAS operating, and the second flight was made without the FAS to provide a base line case for comparison. For these flights, the takeoff gross weight of the helicopter was approximately 17,550 pounds, and the center-of-gravity was 6 inches forward of the aft limit.

Control Systems. - The FAS provided a constant longitudinal control force sensitivity or gradient (15 lb. per g) throughout the high speed envelop of the helicopter (80 to 200 knots). Below 80 knots the longitudinal stick force gradient is reduced to provide lighter forces for conventional helicopter operations in this area of low control sensitivity. As part of the FAS, the roll/pitch trim system is a relatively unique system, consisting of two small thumb wheels mounted on the cyclic stick grip. These wheels command position rather than rates. Another feature of the FAS is a positive cyclic stick centering that engages upon landing for ground operations. The lateral control feel is conventional and is supplied by springs and dampers. In the event the FAS fails, the longitudinal control system reverts to the basic helicopter system with viscous damping; the lateral system remains the same. For the second flight without the FAS, both the longitudinal and lateral control characteristics were that of the basic helicopter with damping provided by simple friction, using telex cables. The directional control system was standard and remained constant for all cases.

Several other unique features installed in the helicopter and common to all cases were the "roll feed forward" input to the lateral control system to provide roll quickening and a collective stick shaker to warn the pilot that the maximum rotor loads were being approached in high speed and maneuvering flight. The "roll feed forward" feature reduced the roll time constant by providing a greater roll rate than commanded, which washes out as the desired roll rate is reached. The collective stick shaker system is mechanized through the cruise guide system which measures the rotating pitch link loads of the rotor system and causes the collective stick to vibrate when the maximum loads are approached.

Test Procedure. - During the flights to access the relative benefits of the FAS, the helicopter was flown from hover to 180 KIAS in level and maneuvering flight, but primary emphasis was placed on maneuvers in the 140 to 150 KIAS range. The maneuvers included constant altitude windup turns and symmetrical pullups to approximately 2 g, roll reversals and S turns and simulated gun runs. FAS failures were also evaluated during high speed maneuvering flight.

Hover. - The helicopter was maintained in a stable hover condition with very little control activity required for both cyclic control systems. However, for air taxiing and low speed maneuvering, the basic system was preferred because it provided lighter forces for more precise controllability. The forces associated with the FAS were not objectionable but did increase the pilot workload slightly. The benefits of the roll quickening feature were not apparent in this flight regime.

Roll/Pitch Trim System. - During the acceleration to high speed flight, it was necessary to continuously trim the aircraft nosedown, indicating positive speed stability provided by the FAS. The location of the pitch trim wheel on the cyclic stick grip was found to be reasonable, and the trim sensitivity was adequate for normal airspeed changes. However, during rapid airspeed changes, the trim sensitivity in pitch was found to be too low, especially during diving accelerations. In this case the use of the trim wheel was somewhat restricted because of the necessary push force required on the cyclic stick. The position of the roll trim wheel was inconvenient in that my thumb did not quite reach it with my hand gripping the stick in the normal manner. Because of an apparent lag in the roll trim channel, coupled with the inconvenient location, some difficulty was encountered in achieving the desired roll trim precision. The stick force gradients near trim appeared to be acceptably light, and the aircraft could be controlled adequately with little effort with the aircraft slightly out of trim. Therefore, precise trim is not required as it is in most conventional helicopters where a slightly out of trim condition necessitates a considerable force: Improvements in the FAS trim system are recommended, but it is a significant advancement over the usual helicopter trim systems.

Level Flight. - Without FAS the basic control system provides good characteristics at and near one g flight out to the maximum test airspeed of 180 KIAS with no trim requirements. The longitudinal control force sensitivity in level and mild maneuvering flight is quite acceptable; however, the rotor pitch link loads sensitivity increase to the point where very small load factor increments trigger the collective stick shaker at 180 KIAS.

Because of the good control characteristics of the helicopter and no trim requirements, the basic control system is preferred to the FAS for not only low speed maneuvering and hovering but also for level and very mild maneuvering flight out to 180 KIAS. The FAS-off flight was made in very smooth air conditions, and the apparent benefits of the FAS in turbulence were not confirmed. However, it would be reasonable to assume that the FAS would aid the pilot in his attempts to control the aircraft in rough air conditions, especially at the upper end of the airspeed envelope.

Maneuvering Flight. - During more severe maneuvers, the benefits of the FAS became readily apparent. The positive maneuvering stability in terms of cyclic stick force per g provided the necessary cue that has always been missing in helicopter control characteristics for maneuvering flight. Because of the constant level of stick force per g throughout the speed envelope (above 80 KIAS), the pilot is able to quickly and smoothly achieve and hold the desired load factor at any airspeed; however, the force required at load factor levels greater than approximately 1.5 g was considered to be slightly high. Without the FAS, the pilot has trouble relating stick position to load factor, which changes with airspeed, resulting in several step type inputs to ascertain, in a safe manner, the necessary displacement required to command the desired load factor. Also, it is more difficult to maintain a constant g level throughout the maneuver if the airspeed is changing. Without the FAS, the pilot must spend more time monitoring the accelerometer in the cockpit in his search for sufficient cues. For the armed attack mission, the FAS greatly enhances the maneuver capability of the helicopter, and the benefits derived overshadow the minor deficiencies associated with higher stick force gradients and trim requirements in the other flight regimes.

Abrupt rolling maneuvers with the FAS on indicated slightly high lateral control forces, although the control harmony with the longitudinal forces was good. The effects of the roll quickener enhanced the initial response, but the maximum rolling rates were not as high as expected (with nearly full lateral stick displacements). These abrupt rolling maneuvers produced a considerable amount of adverse yaw, but because of the somewhat limited roll rates, pedal coordination was not overly difficult: However, too much attention was required in the cockpit monitoring the sideslip indicator during power changes as well as during maneuvers.

FAS Failures. - Full hardover failures were introduced in level and maneuvering flight. The reaction of the helicopter to the failures in level flight was totally insignificant. The aft hardover during a windup turn caused the stick force to lighten, but was immediately recognizable and controllable with very little overshoot in g.

Collective Stick Shaker. - Although the collective stick shaker is not an intregal part of the FAS, it is considered to be a major contribution, together with the FAS, toward a total heads-up capability in providing feel cues to the pilot. These cues enable him to perform maneuvers safely without having to monitor cockpit instruments. As mechanized in the S-67, the collective stick shaker system warns the pilot that maximum rotor loads are being approached. It is very natural to lower the collectives to alleviate the problem, but when the system is deactivated, the pilot does not know to what position the collective was lowered and must look at the torque indicator to get this information. It would be most beneficial if the system were expanded to provide this information so that the collective could be maintained in an optimum position at all times to insure maximum rotor performance.

Without the collective stick shaker system, the cruise guide indicator had to be monitored at all times during maneuvers, and there was a tendency to reduce the intensity of the maneuver. Also, there was a tendency to lower the collective too far and reduce the performance capability of the rotor.

Summary. - The overall flying qualities of the basic S-67 is the best of any helicopter I have flown, and with the addition of the FAS and collective stick shaker warning system, it represents a definite advancement in the state-of-the-art. The deficiencies noted were minor except for the rather severe rotor loads restriction during high speed maneuvering flight. Since the rotor loads problem is the limiting factor in this aircraft, it is felt that the full benefits of the FAS were not realized throughout its speed envelop. Also, the advantages of the FAS would be more apparent in other helicopters with degraded flying qualities and in compound helicopters capable of much greater speeds.

Pilot Number 3: Mr. Duane R. Simon, Eustis Directorate, USAAMRDL

I. Scope

My evaluation of the Feel Augmentation System (FAS), being comprised of only two brief flights in the S-67, reflects impressions that are admittedly subject to the influences of "the learning curve"; however, certain aspects and effects of FAS were clearly discernible. Both flights were conducted from the copilot/gunner's station with the contractor pilot seated in the aft seat acting as safety pilot. The scope of the evaluation comprised wings level flight to 200 Knots Indicated Airspeed (KIAS), maneuvering flight to 85° of bank, dive angles to 40°, and normal accelerations from 0.3 to 2.4 g's. Takeoff gross weights were approximately 17,000 pounds and the center of gravity was two inches aft of the mast centerline. Significant maneuvers were symmetrical pullups, windup turns, and simulated "gun runs" demanding essentially an eyes out of the cockpit technique. Most of the dynamic maneuvers were conducted in the 120 to 160 KIAS speed range.

II. Maneuvering Stability

The artificial cyclic stick forces which provided the classical maneuvering stability (stick force per g) were a definite aid in commanding a given input and controlling the helicopter. This was especially apparent during the pullups from the relatively steep dive angles encountered in the gun runs. The absence of the stick force per g cue during the second flight seemed to reduce my confidence in controlling the aircraft's pitching motion relative to the rotor control structural limits, as displayed on the Cruise Guide Indicator (CGI). Without FAS the pullups required much more attention and caution than that required with FAS; i.e., it seemed that the cyclic inputs were exploratory in nature while the results of these control inputs had to be monitored very closely on the CGI. The kinesthetic cue of normal load was not sufficient to allow the pilot to properly control the rotor structural loads since the CGI was much more sensitive than the "g meter". Additionally, the airframe vibrations usually associated with high rotor loads are not present in the S-67, so the problem became one of having to look at the CGI to properly fly the aircraft. The FAS appeared to be an effective answer to the problem.

III. Stick Shaker

The maneuvering envelope of the S-67 is based upon collective pitch where load factor varies inversely with collective for speeds above approximately 100 KIAS. The collective stick shaker was a great help in signalling the onset of high rotor loads and indicating approximately where the collective pitch stick should be positioned for a given maneuver.

This indication was only approximate, however, because, in the flight environment the shaker action was sensed as being either ON or OFF. Some frustration was experienced during maneuvering in coordinating cyclic and collective pitch. The frustration probably stemmed from a tender to "hunt" for optimum collective settings while trying to compensat, or correlate to some degree with longitudinal cyclic pitch. For airspeeds beyond approximately 100 KIAS the collective stick had to be lowered from that required for cruising flight to a setting appropriate for the particular maneuver. This task involves either knowing what the maneuvering collective pitch setting should be, physically lowering the stick to this setting using the engine torque meters as a reference, and finally executing the maneuver with the cyclic stick or it involves a more simultaneous, coordinated technique where the collective stick is lowered as required in response to cyclic inputs and CGI and/or stick shaker cues. The latter technique is much more desireable for an eyes out of the cockpit mission but stronger and more explicit collective stick feel cues are needed. It is felt that the collective control should be mechanized with a feel augmentation system, patterned perhaps, after the cyclic control FAS. The stick shaker was good but it should be improved upon, especially when considering the optimization of wing maneuvering performance for winged helicopters.

IV. Pitch Sensitivity

The FAS was also designed to deal with the normal helicopter deficiency of increased pitch sensitivity with higher forward airspeeds. However, within the scope of this evaluation, there was no apparent problem in flying the S-67 in terms of cyclic pitch sensitivity (control power per unit of stick input). Notwithstanding, caution was exercised at speeds near 200 KIAS because nearly all the rotor's maneuvering capability was utilized in providing forward thrust; therefore, the collective stick had to be lowered before making any aft or lateral cyclic inputs. Here again, arises the importance of applying some sort of FAS to the collective system.

V. Trim System

The idea of using trim wheels, ala the F8 crusader, in lieu of the conventional "coolie hat" or "press-to-release" trimming systems is judged to be a very good one even for ordinary bungee or spring type trim systems. It allows the pilot to trim off the stick forces at any rate he desires; i.e., very slowly for minute trimming as in cruise or rapidly to compensate for large sudden trim changes as may be encountered in translation. The longitudinal trim system that was mechanized for the S-67 needed a gain change to lessen the amount of wheel motion required per pound of force and the longitudinal wheel should be repositioned within the stick grip to enhance its ease of operation.

VI. Static Stability

The FAS was programmed to provide a rather steep gradient of apparent longitudinal stick-free static stability (stick force versus airspeed).

Although the slow trim rate (gain) caused excess trimming as a function of airspeed, it is felt that a helicopter such as the S-67, which is designed to maneuver and deliver weapons on a target in a diving attack fashion, should possess a near neutral gradient. This also applies to the directional mode.

VII. Failure Modes

Three types of FAS failures were demonstrated. (1) a FAS actuator hardover in cruising flight, (2) a sudden loss of stick forces in a 2g turn, (3) and a simulated pilot failure where the stick was released when in a 2g turn. All induced failures were mild and tractable. The amount of transient stick reaction following the hardover failure was just enough to indicate to the pilot that the system had malfunctioned without being serious enough to bother him. The second type failure, initiated at 155 KIAS, induced about a quarter inch aft cyclic movement when the stick force went from 13 pounds to zero but the transient was easily nullified and there was only a slight increase in normal load. In the third case the stick was intentionally released while applying 16 pounds of aft cyclic force in a 60 degree banked turn. The stick moved forward approximately 2 1/2 inches and normal load diminished from 1.8 to 0.5g in about 1 1/2 seconds. While this appears to constitute an uncomfortable reaction, it was actually suprisingly docile.

VIII. Control Harmony

Longitudinal and lateral control harmony provided by the FAS appeared good although in the 120-160 KIAS speed range the roll forces seemed lighter than those in pitch. From a pilot workload standpoint; however, this pilot would prefer lighter longitudinal maneuvering stick forces, perhaps on the order of 12-15 pounds per g. Also, in connection with good control harmony, there appeared to be a need for increased roll damping.

IX. Summary

Within the scope of this evaluation, the cyclic FAS significantly enhanced the maneuvering characteristic of the S-67 even though the S-67 does not exhibit either a strong "dig in" tendency or the adverse sensitivity problems which plague most helicopters at higher forward airspeeds. Personal flight experience in aircraft such as the XH-51A Compound, UH-1 Compound, NH-3A, CH-53 in or near the 200 knot regime has clearly exemplified the need for effectively desensitizing the controls as a function of airspeed. The scheme of accomplishing this with artificial stick forces (FAS) appears to be a very attractive solution and it provides the means of introducing a positive maneuvering stability force gradient without disturbing the integrity of a given control system. The flight evaluation revealed that the collective pitch control requirements were just as stringent and demanding as the longitudinal cyclic control requirements with respect to properly controlling the helicopter in maneuvering. The collective stick shaker worked well; however, it did not provide enough information for the pilot to properly fly a typical eyes out of the cockpit mission. Additional collective stick feel augmentation would certainly enhance the system.

COMPARISON OF FLIGHT EVALUATION RESULTS WITH FLIGHT TEST DATA

The evaluation of FAS was based heavily on subjective pilot opinion. Flight data determined the load factor force gradient and the aircraft response and control motions after simulated failures. On the other hand, evaluation of ease of control during maneuvers, smoothness of control during maneuvers, trim system operation, and the ability to fly "heads-up" maneuvers was based primarily on pilot opinion.

The mild shutdown characteristics of FAS were confirmed by all three Government evaluation pilots. According to the Sikorsky test pilots and the evaluation pilots, the stick motion following simulated hardovers never exceeded 0.5 inch, less than 5 percent of the total control travel. This result is confirmed by the results shown in Figure 14, in which the stick displacement was 0.3 inch for a hardover in hands-off level flight. Similar results for simulated hardovers were obtained during the Government evaluation flights. Prior to the flight test program, it was thought that an aft hardover during a high speed, high g turn would have the worst effect on aircraft safety, since even a small aft stick input can cause a large increase in rotor control loads. However, simulated aft hardovers during 2 g turns at 170 knots resulted in a rapid and smooth transition to the damper mode with little disturbance to the flight path. The pilot quickly became aware of the loss of FAS and was able to maintain his flight condition while correcting for the increasing control loads.

The correlation between pitch control forces and load factor in steady maneuvers was generally confirmed by all three Government evaluation pilots. They also thought that the force gradient was too high because of the effort required to fly the aircraft to the extremes of its maneuvering envelope. Figures 11 and 12 show that the control force did correlate with load factor during steady maneuvers, and that the force gradient varied from 18 pounds per g at 100 knots to 25 pounds per g at 170 knots. This variation of force gradient was designed into the FAS to reduce the pilot's ability to make control inputs at high speeds when the control loads may increase rapidly for small control inputs. If desired, the force gradient could be held constant with airspeed by adjusting the pitch rate gain function. The Government evaluation pilots felt that, for 1.0 g to 1.5 g load factors, the stick forces were reasonable, but for higher load factors the forces were too high. There is, theoretically, no reason to suggest that the force gradient produced by FAS was higher for high load factors than for low, and the data of Figure 11 were insufficient to confirm this nonlinear characteristic. However, it was felt by the Sikorsky pilots that reducing the force gradient to the 10 to 15 pound per g range would eliminate the complaint of high forces at high load factors. All pilots agreed that the load factor feel bled off gradually below 80 knots. The characteristic is only approximated in Figure 12, since no data points were taken in the transition regime. This reduction of force gradient from the maneuvering level to zero for hover was designed into FAS by the gain functions of Figure 8. Furthermore, the pilots found that the control forces during hover were too high. They felt hover forces should be reduced to allow free stick movements and minimize pilot effort.

The changes in stick forces experienced when initiating a maneuver or when changing the maneuvering condition did not always correlate with the load factor existing at the instant the inputs were made. Actually, the control force generally built up upon the initial motion of the stick and before the aircraft pitch rate began. Figure 9 shows that, as the stick was moved, the force increased or decreased and then remained steady as the load factor increased or decreased to the desired level. This characteristic, in effect, provides anticipation for the load factor that will result from a control input. This lead in the force level did not appear to detract from the load factor feel, and it helped provide the smooth transition from level flight to maneuvering flight.

Probably the two most important and subjective results of the addition of the FAS were (1) a great increase in pilot confidence during a maneuver, and (2) a significant reduction in pilot attention to cockpit instruments during maneuvering flight.

The control harmony provided by the roll FAS, in the presence of the high pitch forces, was judged adequate by all three Government evaluation pilots. However, all pilots agreed that the damper force was too high (2.0 pounds per inch per second). The Sikorsky pilots agreed that roll forces were high and that a reduction of the pitch force gradient would make possible a lower roll damper force. After flying the FAS with and without roll quickening, the Government evaluation pilots agreed that roll quickening was necessary since it reduced the initial roll stick motions required for roll inputs, thereby reducing the roll damper force. However, the roll quickening destabilized the aircraft when roll trim changes were made.

The thumbwheel position trim system was an improvement over the conventional beeper trim system. The pitch trim characteristics were good except during rapid changes in airspeed, when several thumbing motions were required to maintain the stick in trim. Six full thumbwheel rotations, or 18 normal thumbing motions, are required to trim the stick from full aft to full forward position. The sensitivity of the thumbwheels should be increased to reduce the thumbing motions required to trim the stick. The force levels around the trim point were acceptable in both pitch and roll.

All the Government evaluation pilots complained about the roll trim. When trimming the stick in roll, the stick would lag behind and then overshoot a change in trim point. The lag and overshoot, combined with the roll quickening, left the pilots in a limit cycle about the trim point in attempting to establish trimmed flight. This sloppy roll trim capability was also observed by the Sikorsky pilots and was probably the result of four factors: (1) the 10-percent-per-second maximum trim rate of the AFCS trim servo used to implement roll trim,(2) resulting lag behind the command trim position because the pilot could command a faster rate with his trim knob, (3) hysteresis in the trim servo position control loop, and (4) a trim spring breakout force insufficient to keep the stick in the trim position at all times. However, the ability to move the stick smoothly through the trim point eliminated any chance of pilot-induced oscillation and reduced the necessity of establishing a precise trim point.

The collective stick shaker provided a cue to increasing rotor loads that reduced the attention of each of the Government evaluation pilots to the cruise guide indicator. They began to feel vibrations at a 25 percent reading and could adjust the collective stick to relieve the rotor control loads. However, they still had to resort to the cruise guide indicator to determine the magnitude of collective adjustment required. The Sikorsky pilots, because of their familiarity with the aircraft, were able to control rotor loads almost without looking at the cruise guide indicator.

The Government pilots felt that the stick shaker seemed to be an on-off device; they were not able to use the proportional range of vibration amplitude shown in Figure 15. This is due to the sensitivity of control loads above the operating load level of 25 percent. Above the 25 percent level the cruise guide increases quickly to cause maximum vibration. Even though the Government pilots wanted the stick shaker to have a greater amplitude, the stick shaker flown on the S-67 made possible a significant step toward the "heads-up" maneuvering capability.

COMPARISON OF CONTROL CHARACTERISTICS

S-67 control characteristics without FAS differ from the characteristics with FAS. Without FAS, the pilot feels drag friction forces in the control system. With FAS, forces applied to the pitch cyclic control are related to a maneuvering load factor. The components of the cyclic stick forces measured in various flight regimes for the S-67 with and without FAS are compared in Table III. Each control system is described below to enable a comparison of the manner in which differing control characteristics affect the pilot.

STANDARD S-67 WITHOUT FAS

The standard S-67, as flown during the evaluation, does not use a trim system like those used in other Sikorsky helicopters. Control feel is provided by adding friction to the control system. Cyclic stick forces are constant and opposite to the direction of motion, but do not depend on stick rate or displacement from trim. The friction level is sufficiently high to prevent cyclic stick motion during hands-off flight. Since the stick feel is in no way related to the load factor or control loads, the pilot is required to monitor the cruise guide indicator during maneuvering flight to determine control loads. To maintain normal control loads, the pilot should lower the collective, thereby increasing the wing's share of the maneuvering load.

Conventional Sikorsky helicopters (H-53, H-3 or H-54) use a spring and a beeper trim system to provide a cyclic control feel system. The force the pilot feels in these aircraft is proportional to the displacement of the stick from trim. The force rate is 0.8 pound per inch. To provide positive centering of the stick for hands-off flight, the spring has a breakout of approximately 1-1/2 pounds. To change the trim position, the pilot pushes a coolie hat button on his cyclic stick, in the direction he wants to trim. The stick is driven at a constant rate until the pilot releases the button. This system is also available in the S-67 but was not connected during the FAS evaluation program. Maneuvering flight with this system, if provided in the S-67, would require the same attention to cruise guide as the friction force system.

S-67 WITH FAS

With FAS, pitch cyclic stick feel is a force proportional to load factor, stick rate, and stick deflection. Drag and friction forces, somewhat smaller than those of the drag friction system, are also present. The addition of these forces provides a smooth feel, even when the stick is moved through the trim position. Reduction of the conventional roll trim spring breakout level, plus the addition of the damper, permits smooth stick movement through the roll trim point with very little force discontinuity. The pitch FAS provides stick forces essentially proportional to load factor in the maneuvering speed range (100 knots to V_{max}), while the roll FAS provides trim position and control harmony. The FAS also provides a warning of increasing control loads by a collective stick shaker.

TABLE III. CONTROL FORCES OF THE CONTROL SYSTEMS

Flight Regime	Force Component	S-67 FAS		S-67 Standard	
		Pitch	Roll	Pitch	Roll
Taxi	Total Breakout (lb)	6.0	1.1	2.0	1.50
	Drag Friction (lb)	2.0	.35	2.0	1.50
	Spring (lb/in.)	0	.5	-	-
	Viscous Damper (lb/in./sec)	1.50	2.0	-	-
	Load Factor (lb/g)	0	-	-	-
Hover	Total Breakout (lb)	2.0	1.0	2.0	1.50
	Drag Friction (lb)	2.0	1.0	2.0	1.50
	Spring (lb/in.)	0.0	0.0	-	-
	Viscous Damper (lb/in./sec)	1.50	2.0	-	-
	Load Factor (lb/g)	0.0	-	-	-
Cruise (140 kn)	Total Breakout (lb)	2.0	1.1	2.0	1.50
	Drag Friction (lb)	2.0	.35	2.0	1.50
	Spring (lb/in.)	5.0	.5	-	-
	Viscous Damper (lb/in./sec)	3.0	2.0	-	-
	Load Factor (lb/g)	20	-	-	-
Vmax (170 kn)	Total Breakout (lb)	2.0	1.1	2.0	1.50
	Drag Friction (lb)	2.0	.35	2.0	1.50
	Spring (lb/in.)	6.50	.5	-	-
	Viscous Damper (lb/in./sec)	3.0	2.0	-	-
	Load Factor (lb/g)	25	-	-	-

Maneuvering flight with the FAS requires more force than the standard S-67 system, but the presence of the forces from load factor and stick motion results in smooth, well controlled maneuvers. Combined with warning by the collective stick shaker of increasing rotor loads, the FAS permits more attention outside the cockpit.

With FAS, the cyclic stick trim position is determined by the position of pitch and roll trim wheels in the cyclic stick grip. These trim wheels are rotated by thumb motion. The evaluation pilots' comments in comparing this system with the standard coolie hat trim system were that the FAS trim system was (1) a "step in the right direction," (2) a "significant advancement," and (3) a "very good one".

CONCLUSIONS

The stick force per g provided by the pitch FAS increased pilot confidence and reduced the pilot's need for concentration on the load factor indicator during maneuvers. Moreover, the collective channel of FAS (collective stick shaker), with its warning of increased rotor loads, permitted more attention outside the cockpit. Although the stick shaker did not quantify the rotor load level, the combination of constant stick force per g in the pitch cyclic control and rotor load warning in the collective control is a step toward achieving "heads-up" maneuvering capability.

The pitch FAS, with its relatively constant stick force per g, provided a force gradient that varied from 18 pounds per g at 100 knots to 25 pounds per g at 170 knots. This force gradient was too high at all airspeeds and should be reduced to 10 to 15 pounds per g. The roll damper force should also be reduced from its present value of 2.0 pounds per inch per second.

The failure characteristics of FAS were very mild and easily met the requirements of MIL-H-8501A. Cyclic stick pitch movements following 100 percent single FAS actuator hardovers were always less than 0.5 inch regardless of flight conditions.

The thumbwheel position trim system is an improvement over the conventional beeper trim system. However, its low sensitivity in pitch required too many thumbing motions during rapid changes in airspeed. The roll trim response was sluggish and would overshoot the desired position.

APPENDIX I

FAS FAILURE MODE ANALYSIS

POSSIBLE FAS FAILURES

This failure mode analysis of the FAS considers primarily the pitch channel. The collective channel of FAS cannot introduce contr l signals into the helicopter flight control system, since it vibrates the stick in a plane perpendicular to the control motion. The collective stick shaker can fail on, off, or at low operating level. Failure of the shaker to operate properly would require the pilot to monitor the cruise guide indicator during maneuvers.

The roll channel of the FAS uses the S-61 AFCS servo trim actuator for the roll stick trim function. The runaway rate of the trim actuator is 10 percent per second, which is within the FAS design requirement for failure rate. The hydraulic damper, which provides the FAS roll damping feel, is conne ted to the cyclic stick in series with an override spring capsule. A jam of the hydraulic damper can be overridden by moving the stick against the override spring. Turning the stick trim system off would put both the AFCS trim spring and the damper into the release, or bypass, mode.

The pitch FAS fault detection system is designed to shut down the pitch FAS channel when any single component failure results in a differential output of the dual pitch channel actuators. It is assumed that simultaneous identical failures in both FAS pitch channels will not occur since they cannot be detected by monitoring the outputs of a 2-channel redundant system. A 5-percent difference in the outputs of the two channels was established as the minimum band for tripping the fault-detection system. The band was selected to be large enough not to cause nuisance shutdowns due to noise and built-in gain variations, but small enough to shut down the FAS before dangerous stick motions result if a failure occurs. The effect of hardover failures varies with the amplitude of the hardover and the flight condition. Table IV summarizes the various possibilities.

Some types of specific component failures that might occur are described in the following paragraphs. The operational amplifiers, resistors, capacitors, and electromechanical servo-multiplier mentioned in the description are all part of the FAS electronics. The electromechanical servo-multiplier is a motor which rotates as airspeed changes. The motor shaft is used to turn potentiometer shafts to vary the potentiometer settings. This is the device used to vary the pitch FAS gains with airspeed. Each gain is varied by an individual potentiometer.

1. Faulty operational amplifiers may become hardover, dead, intermittent. Failure of any operational amplifier in a signal path causes rapid shutdown of the system because of the resulting differential force output.

TABLE IV. EFFECTS OF WORST-CASE FAILURES WITH FAS		
Failure Case	Flight Condition	Typical Results
1. 100% force hardover in one actuator fwd or aft	Hands-off cruise	Hardover servo accelerates the yoke, while the other actuator accelerates in the opposite direction. Some net force accelerates the control stick. Shutdown occurs quickly (100 milliseconds) to prevent large stick motion.
2. 100% force hardover in one actuator fwd or aft	Hands-on cruise	Similar to case 1, but the pilot's hand increases the effective mass of the stick so it moves less before shutdown.
3. Above 10% but less than 100% single hardover fwd or aft	Hands-off cruise	Actuator acceleration is less, and the other actuator still moves in the opposite direction. Shutdown occurs later but with stick displacement similar to cases 1 and 2.
4. 100% aft force hardover in one actuator	Holding 20-30-pound aft stick force in a turn	Force is in the direction the pilot is pulling the stick, and the actuator and stick accelerations are greater than for cases 1 and 2. Shutdown occurs, but additional stick motion may result as the pilot moves stick against the damper before he is able to relax his pull force.

2. Resistors or capacitors with a shorted or open circuit cause differential gains between corresponding signal paths, and shutdown occurs when the differential force exceeds the 5-percent threshold.

3. The electromechanical servo-multiplier can become inoperative at any airspeed setting, or run away to maximum or minimum setting. In any case, the result is a slow change in the force gradient rather than a hardover, since the gearing is such that 5 seconds are required for full change of the gains. This failure is very mild and undetected. The individual potentiometer assemblies and wiring preclude any sort of simultaneous potentiometer failures. Single potentiometer failures from shorting or open circuit result in gain differences, and shutdown occurs at the 5-percent threshold.

4. Failure (shorting or open circuit) of a trim wheel renders trimming inoperative at that grip only. If the pilot discovers an inoperative trim, manual FAS release can be used to remove stick forces due to an out-of-trim condition. The trim module (see Figure 6) is dual, and failure of any component results in a differential trim reference. The system will shut down at a 5-percent differential force.

5. Sensor failure (stick position or rate gyro) results in shutdown when the differential force output exceeds 5 percent. Failure of the airspeed transducer will cause only a slow change in the force gradient, and no shutdown will occur. The airspeed transducer converts the pneumatic airspeed signal from the pitot sensor to an electrical signal to drive the electromechanical servo-multiplier.

6. Power failures could cause loss of one or more of the following:

   28 volt dc power

   ±15 volt amplifier power supplies

   ±15 volt motor power supplies

   115 volt ac power

   hydraulic supply pressure

   Any of the above conditions will cause shutdown.

7. A FAS actuator failure will cause system shutdown when the differential force exceeds 5 percent. Hydraulic pressure is removed from both actuators, and they remain in the passive damper mode.

8. A jammed actuator results in yoke tilt when the stick moves, and the remaining actuator will be shut down. Some stick travel (about 50 percent) is allowed by tilting of the yoke. Beyond this, deflection of the override spring capsule (see Figure 6) allows complete travel.

9. Simultaneous jamming or hardover of both actuators will not result in shutdown. However, the override capsule would deflect to allow stick movement.

EXPERIENCE WITH FAS PROTOTYPE

The FAS prototype design was based primarily upon achieving the functional characteristics and providing flexibility in signals and gains. Considerable emphasis was also placed on providing a shutdown scheme. Since many prototype components were used in FAS, individual component reliability was not studied. Two types of component failures were found in preflight inspections during the development testing:

1. Some operational amplifiers became hardover, or were otherwise inoperative.

2. Two of the potentiometers used in the electromechanical servo-multiplier and the pitch trim module became defective.

All failures of these amplifiers and potentiometers produced force differentials that caused a FAS shutdown or prevented engagement. All these component failures were found and repaired before flight. However, two types of shutdown problems occurred during flights in the development phase:

1. On two flights, FAS shut down after several minutes in the air. No stick force or improper control inputs were experienced. FAS remained in the damper mode and could not be re-engaged, so the flights were terminated.

2. On three flights, FAS would shut down while the pilot was making pitch stick inputs at the beginning of a maneuver. No change in stick force occurred other than the normal transfer to damper mode. FAS could be re-engaged after centering the yoke, so the flights were continued.

Shutdown type 1 was attributed to a drift in the power supply voltage. Laboratory power supplies had been used, and the aircraft vibrations caused a voltage control knob to turn. The control knobs were secured and the problem was eliminated.

Shutdown type 2 was a result of differential forces acting on the FAS yoke. The differential forces were due to one of the FAS servo valves being out of tolerance and unequal seal friction in the actuators. The seal friction could not be remedied without dismantling the entire FAS actuator installation. However, the out of tolerance condition was compensated by applying a correcting electrical current to the servo valve. This reduced the force differentials such that the shutdowns did not occur. The hydraulic portion of the FAS experienced no failures. The three Government evaluation flights with FAS on were conducted with no shutdown problems or failures.

Much care was required in bench testing the dual pitch electronic components to attain simultaneous tracking of actuator outputs within ±5 percent. The electronic portion of the pitch FAS, shown in Figure 2, consisted of 3 electronic circuit boards. The signals of channels 1 and 2 flow simultaneously from sensors, through the 3 circuit boards in sequence, then to the force actuators. Each circuit board, containing identical and separate circuitry for channels 1 and 2, was adjusted to give tracking within ±1 percent during the bench test.

The test box used with FAS was equipped with test points for channels 1 and 2 corresponding to the input and output of each circuit board. The signal levels were monitored with a meter, and a gain difference or otherwise faulty signal could be pinpointed quickly. The faulty circuit board was then returned to the laboratory, where the fault was corrected. All such problems were isolated to a specific circuit board without removing the FAS computer from the aircraft. This method has eliminated the need for an elaborate bench test setup, since only individual circuit boards need be tested. All signals in the FAS electronics were relatively high level (1-10 volts) and primarily dc, so noise and coupling of ac signals were insignificant.

Based on the experience with the FAS prototype, a section is presented in the Appendix on maintenance support requirements.

PITCH CHANNEL FAS ACTUATOR SIMULATION

The pitch channel FAS actuators and electronics were simulated on an analog computer to determine whether the failure and shutdown characteristics would be safe for flight. The block diagram of the simulation is shown in Figure 17.

Pressure valve characteristics, such as pressure loss due to flow rate ($K_a A_p$) and flow limiting at 100 percent per second, were included. Figure 17 shows the simulation block diagram for the actuator, stick, yoke, and electronics. The electronics consist of an electrical spring on the yoke angle in addition to an electrical spring and damper on stick position. The spring on the yoke angle was the predecessor of the detent mechanism. When the magnitude of the yoke angle corresponded to a 10-percent force mismatch, an electronic switch was actuated, and a 20-millisecond time delay simulated the actuation time of the relays and shutoff valves.*

* A 10-percent threshold was used in the simulation to minimize nuisance shutdowns while a 5-percent threshold was used in flight to achieve a quicker shutdown. The actual delay was 40 to 100 milliseconds in flight test.

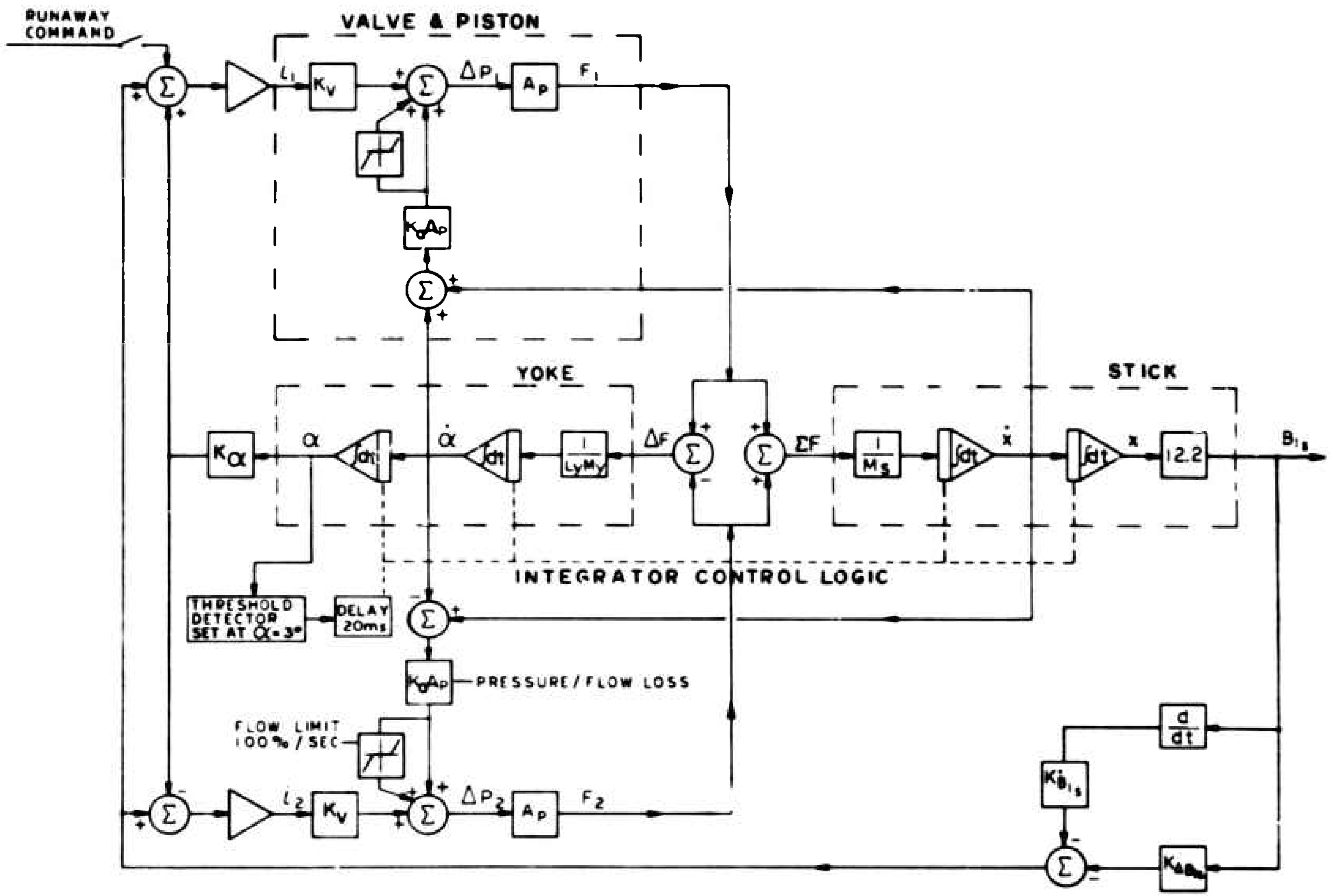

Figure 17. Diagram of FAS Actuators.

The nominal parameters are:

pitch FAS actuator valve gain (K_v)	65.2 psi/ma
actuator piston area (A_p)	.428 in.^{2}
pressure loss due to flow rate ($K_a A_p$)	50 psi/in./sec at servo
yoke tilt feedback gain (K_α)	.3 ma /deg
pitch FAS damper gain ($K_{\dot{B}_{1_s}}$)	1.75 lb/in./sec at stick (.378 ma/in./sec)
pitch FAS spring gain ($K_{\Delta B_{1_s}}$)	0.0 to 10.0 lb/in. at stick (0.0 to .18 ma/in.)
moment arm for force on yoke (L_y)	1.5 in.
equivalent mass of longitudinal control stick and linkage (M_s)	.96 lb-sec^2/in. at servo
equivalent inertia of yoke (M_y)	.0015 lb-sec^2/in. at servo

The pitch channel actuator simulation was used to evaluate the stick motion resulting when simulated hardover inputs are applied to a single FAS actuator. The effects of the various parameters on the magnitude of this stick motion were studied. Actuator seal friction and backlash in the linkage were neglected in the simulation. An actuator hardover was initiated by causing number one actuator to accelerate to 100 percent per second, its maximum rate. Failure detection occurred when the yoke angle reached 3 degrees, and shutdown was simulated 20 milliseconds later by switching the computer to hold mode. Higher stick displacement and stick damper feedback gains tended to restrain the stick motion by feeding into the operative actuator a signal that caused it to move in the opposite direction. The yoke angle then reached the 3-degree threshold sooner, and shutdown occurred with less stick motion. Figure 18 shows a transient for a displacement gain, $K_{\Delta B_{1_s}} = 0$, and a damper gain, $K_{\dot{B}_{1_s}} = 1.75$ pounds per inch per second. This damper gain is approximately that used in the flight test during hover. The yoke tilt feedback gain is $K_\alpha = 0.20$ ma per degree, so at the 3-degree threshold, the feedback is 0.6 ma, close to 10 percent of the total output of 8.0 ma. Figure 18 shows that the total stick displacement was .25 inch in about 100 milliseconds, well within the designed failure envelope. For the flight test, the yoke spring was replaced by the yoke detent, which has a trip level of 20 pounds, or 5 percent of the total actuator output.

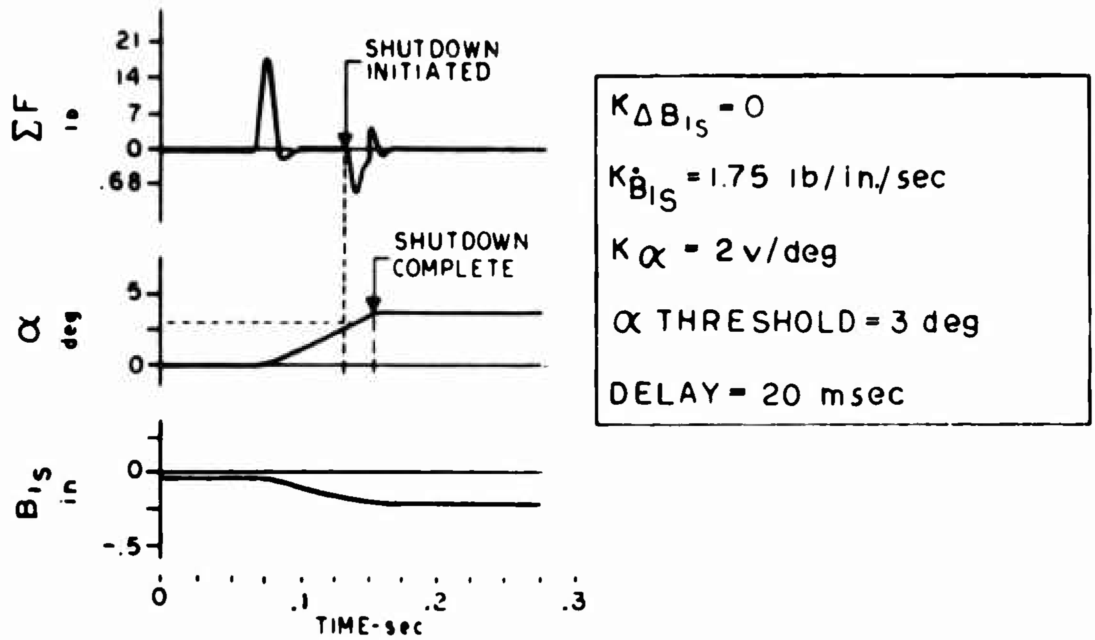

Figure 18. Simulated FAS Actuator Hardover.

APPENDIX II

MAINTENANCE SUPPORT REQUIREMENTS

Two maintenance problems were experienced with the prototype FAS. One problem was the requirement of ±1 percent tracking of the dual pitch channel outputs. Since the fault-detection threshold is ±5 percent, this close tracking was required to prevent nuisance shutdowns. Careful trimming of electronic signal gains and biases was required during the bench testing of each module. Bias in the FAS servo valves and seal friction in the actuators also caused some difficulty in achieving satisfactory tracking. The other problem was the low reliability of the operational amplifiers and servo-multiplier potentiometers, a result of using prototype quality components. The roll channel FAS was not dual and required neither precise calibrations nor experienced failures during the testing.

To reduce the maintenance requirements for the production FAS, the pitch channel will be designed for easier tracking and the components will be selected for greater reliability. For ease of tracking, the electronic modules of each stage will be designed with both channel 1 and electronics on the module. Therefore, only one module need be tested for each stage in the dual gain paths. By simultaneoulsy monitoring channels 1 and 2 with a simple test set, a technician will be able to quickly pinpoint the tracking problem without reference to data on gain calibrations or detailed test procedures.

For improved reliability, relays will be replaced by all solid-state logic. The servo-multiplier assembly may be retained but it will be equipped with improved reliability potentiometers. The operational amplifiers will be an improved model with much higher reliability than the reliability of those used in the FAS prototype. In addition, the pitch FAS actuators can be simplified. Both actuators, along with shutdown valves and yoke mechanism, should be enclosed in a single block. This improvement would eliminate some electronics, simplify the hydraulics, and reduce the weight of the actuator assembly.

To eliminate the need for maintenance support equipment, a built-in test (BIT) function could be added to the pitch FAS. The dual channel nature of the pitch FAS lends itself to the addition of a built-in test function. This BIT system would be a self-contained signal simulator for each path with level monitors to feed BIT logic that could indicate if a failure exists and on which module.