NASA Contractor Report 166009

Development and Flight Evaluation of an Augmented Stability Active Controls Concept

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Executive Summary

Wiley A. Guinn

LOCKHEED-CALIFORNIA COMPANY
BURBANK, CALIFORNIA 91520

CONTRACT NO. NAS1-15326
NOVEMBER 19, 1982

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DEVELOPMENT AND FLIGHT EVALUATION OF AN AUGMENTED STABILITY ACTIVE CONTROLS CONCEPT - EXECUTIVE SUMMARY

W. A. Guinn

Lockheed-California Company
Burbank, California

SUMMARY

A pitch active control system (PACS) was developed and flight tested on a wide body jet transport (L-1011) with a flying-stabilizer/geared-elevator.

Modifications to the baseline aircraft included installation of the PACS, addition of a transferable water ballast system for center of gravity (c.g.) management, and downrigging the geared elevator 0.09 rad (5 deg) to provide nose down control authority for aft c.g. flight conditions. The PACS consisted of a lagged pitch rate damper to control the short period mode and a compensating feed-forward loop to enhance the control column feel characteristics.

The flight test program was conducted with three different pilots who used Cooper-Harper ratings to quantitatively express their opinion of the aircraft longitudinal handling qualities. The reference flight condition for handling quality evaluation was at 25 percent mac c.g. with PACS off. Tests were performed at high speed flight conditions within the linear stability region at c.g. locations of 25, 35, 37, and 39 percent mac with PACS on and off. The handling qualities with the c.g. at 39 percent mac (+1 percent static stability margin) and PACS on were judged to be as good as the handling qualities with the c.g. at 25 percent mac and PACS off.

This program has flight demonstrated that a pitch active control system can be designed for a wide-body jet transport which maintains the same handling qualities while the static stability margin is reduced from +15 to +1 percent mac. This technology could now be applied to current aircraft to achieve approximately 2 percent fuel savings for linear stability conditions.

INTRODUCTION

Program Objectives

In the past decade (1972 to 1982) fuel cost has increased from approximately 25 percent to 60 percent of aircraft direct operating cost (DOC). This fuel cost trend was forecast in the early 1970s. Therefore, in 1975 the U.S. Congress requested NASA to set up a program to develop fuel saving technology for commercial transports. Thus, the NASA Aircraft Energy Efficiency (ACEE) program was initiated in 1976.

The purpose of the ACEE program is to develop fuel saving technology for commercial transports. The primary goal of the current study was to develop a pitch active control system (PACS) that will maintain good aircraft handling qualities for relaxed static stability (RSS) flight conditons.

Rationale for Program

Relative to current subsonic commercial jet transports (e.g. Lockheed L-1011); reduced area horizontal tail, flight with more aft c.g. locations, and advanced technology wing configurations can result in significant fuel savings. Potential fuel savings are reduced area tail (3 percent), more aft c.g. (2 percent for current wing and 4 percent for advanced wing concepts). The advanced wing configuration, which is not addressed during this study provides a fuel savings that is on the order of 10 percent. Implementation of these concepts to maximize fuel savings reduces the static longitudinal stability and degrades the aircraft handling qualities. Utilization of a PACS is a way to maintain the handling qualities when the fuel saving concepts are implemented.

Background

In 1977 Lockheed received an ACEE program contract for "Accelerated Development and Flight Evaluation of Active Control Concepts for Subsonic Transport Aircraft" (NAS1-14690). The contract resulted in development of an aileron active control system (AACS) which was installed on the Lockheed L-1011-500 in 1980 to allow a 5.8 percent wing span increase and the associated 3 percent fuel savings. Also, studies were conducted to evaluate benefits of a small horizontal tail and a PACS. Piloted flight simulation tests conducted on a moving base simulator showed that a lagged pitched rate damper maintained good flying qualities of the baseline airplane to near neutral static stability in heavy turbulence. This piloted simulation results provided the basis for the current program (NAS1-15326) which was initiated in 1978. In May 1980 the program was restructured to test the PACS for RSS by moving the c.g. aft to within +1 percent of the neutral point.

1. OVERVIEW OF PROGRAM

During a previous NASA program (NASA Contract NAS1-14690), a PACS preliminary control law was developed and tested on the L-1011 visual flight simulator (VFS) to show handling quality benefits of an active control pitch augmentation system for flight at relaxed static stability conditions. The scope of this program (NASA Contract NAS1-15326) was to refine the simulated control laws, develop a PACS system, and demonstrate its capabilities by flight tests.

The activities required for development and test of the PACS are shown by the block diagram in figure 1. A synopsis of the major activites accomplished under each of the major headings shown in the figure are discussed below.

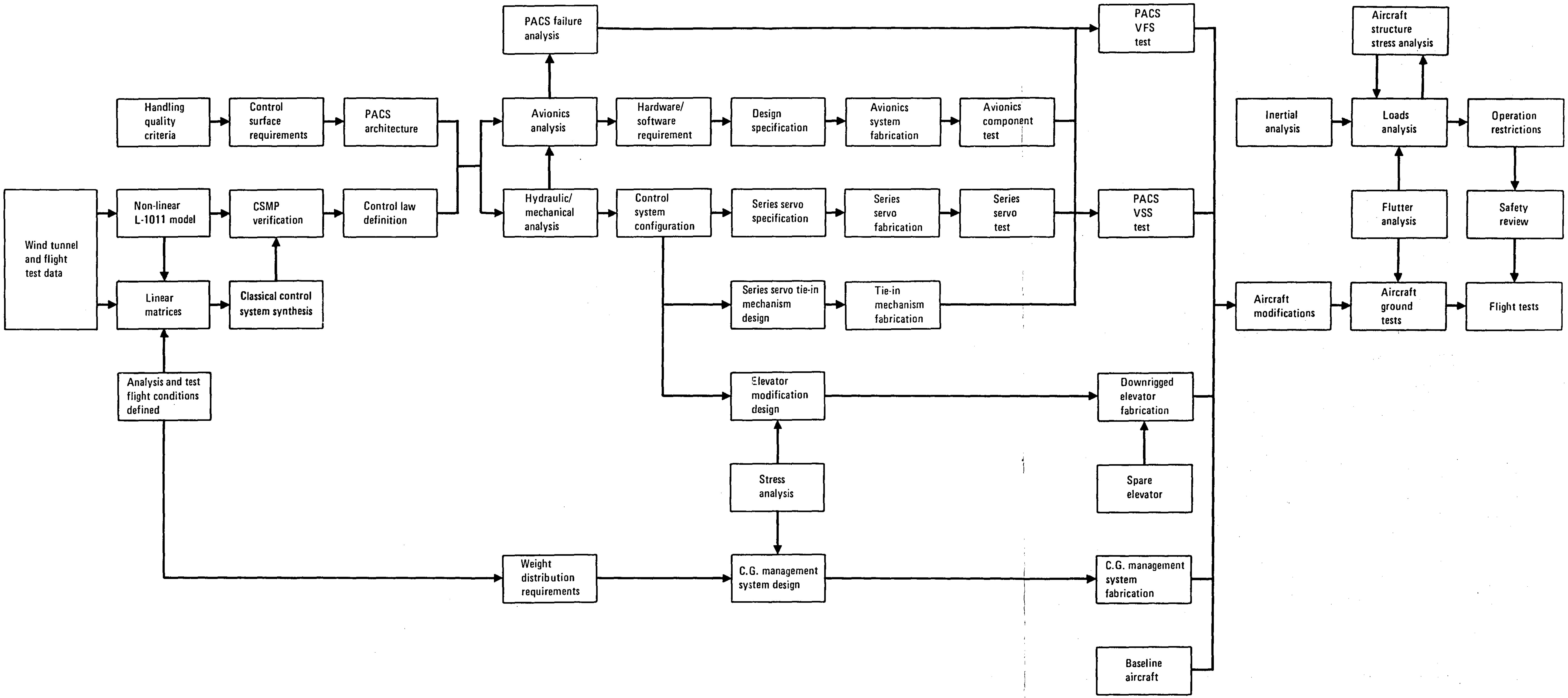

Figure 1. - Near-term PACS program development activities.

1.1 Control Law Development and System Architecture

Handling qualities criteria and flight conditions for evaluation of the PACS were established. Then, control surface rotational displacements and rates were determined. Wind tunnel tests were performed to verify that a 0.09 rad (5 deg) downrigged elevator provided sufficient nose down control for the aft c.g. flight conditions and to determine aerodynamic loads and hinge moments. Concurrent efforts were directed toward refinement of the PACS control law and development of the PACS configuration. Existing control system synthesis computer programs were utilized for control law refinement and continuous system modeling programs were used for analytical verification. The PACS configuration was designed to be compatible with the basic L-1011 control system and to utilize available PACS components. The architecture was developed by determining the number of redundant components needed to satisfy reliability and safety requirements.

1.2 Component Design, Fabrication, and Test

The components to be developed were divided into four categories: Avionics system, series servo, c.g. management system, and downrigged elevator.

Avionics system mechanization required defining the system architecture. Sensors, digital computers, and associated software, and the test pallet were developed into a unified system that had a compatible interface with the electrohydraulic valves and output arm sensors of the PACS series servo. The sensors (pitch rate gyros, column force, and dynamic pressure) were available at Lockheed as were two Collins ACC-201 computers which were modified according to the refined control laws. The computers were bench tested prior to installation on the vehicle system simulator (VSS).

The series servo (National Water Lift 3010000) and the series servo tie-in mechanism designs existed prior to the start of the program. These components were fabricated during the current program and the series servo was bench tested prior to installation on the VSS.

The c.g. management system was assembled from lead ballast and water tanks that were available from the L-1011 development test program. An electrical system was designed and installed to control the water transfer and dumping.

The downrigged elevator counterbalance arms were modified to prevent interference of the counterbalance weights with the stabilizer upper panels. A spare elevator was reworked for this modification.

During the component design, fabrication, and test activities, support was provided by Loads, Vibration, Flutter, Weight, and Safety Groups as required.

1.3 PACS Evaluation Tests

Prior to flight testing, the control laws were implemented on the L-1011 moving base visual flight simulator (VFS) and evaluated by the same three pilots. The test time was about 60 hours.

After tests of the individual PACS components were satisfactorily completed, they were installed on the L-1011 vehicle systems simulator (VSS). The VSS is a full size, rigid body simulator of the L-1011. Actual aircraft parts (servos, surfaces, cables, hydraulic systems, etc.) are installed as they would be on the aircraft. Simulated PACS functional tests were conducted which corresponded to the conditions that were to be flight tested.

1.4 Aircraft Ground and Flight Tests

The PACS, c.g. management system, and downrigged elevator were installed on the aircraft and checked out. A ground vibration test was performed to investigate structural modes of the modified aircraft and coupling of the PACS with the structural modes. Flight tests included a flutter clearance test (15 hours) and handling quality evaluation tests (31 hours) with 25, 35, 37, and 39 percent mac c.g. locations. Cooper-Harper ratings were utilized by the pilots to compare the handling qualities with PACS on and off.

2. AIRCRAFT DESCRIPTION

2.1 Flight Test Aircraft Configuration

A unique version of the L-1011 aircraft was used throughout the PACS program analysis, design, and flight test. Features of the aircraft are shown in figure 2. The test aircraft (S/N 1001) is a basic L-1011-1 with extended-span wing and aileron active control system (AACS) which were installed during a previous contract (NAS1-14690). Modifications during this program include the items shown in the blocks: PACS, c.g. management system, and downrigged elevator.

2.2 Pitch Active Control System (PACS)

2.2.1 PACS configuration. - A simple block diagram of the longitudinal control system of the Lockheed L-1011 aircraft equipped with PACS is depicted in figure 3. The existing control system prior to installation of the PACS is represented by the dashed lines. PACS components and associated signal flow paths are represented by the solid lines. Three types of sensors provide analog signals to the digital computer. These sensors are pitch rate, column force, and dynamic pressure. The computer provides control signals to a limited authority pitch series servo. The series servo output is summed with the pilot input to drive the horizontal power actuator which rotates the stabilizer.

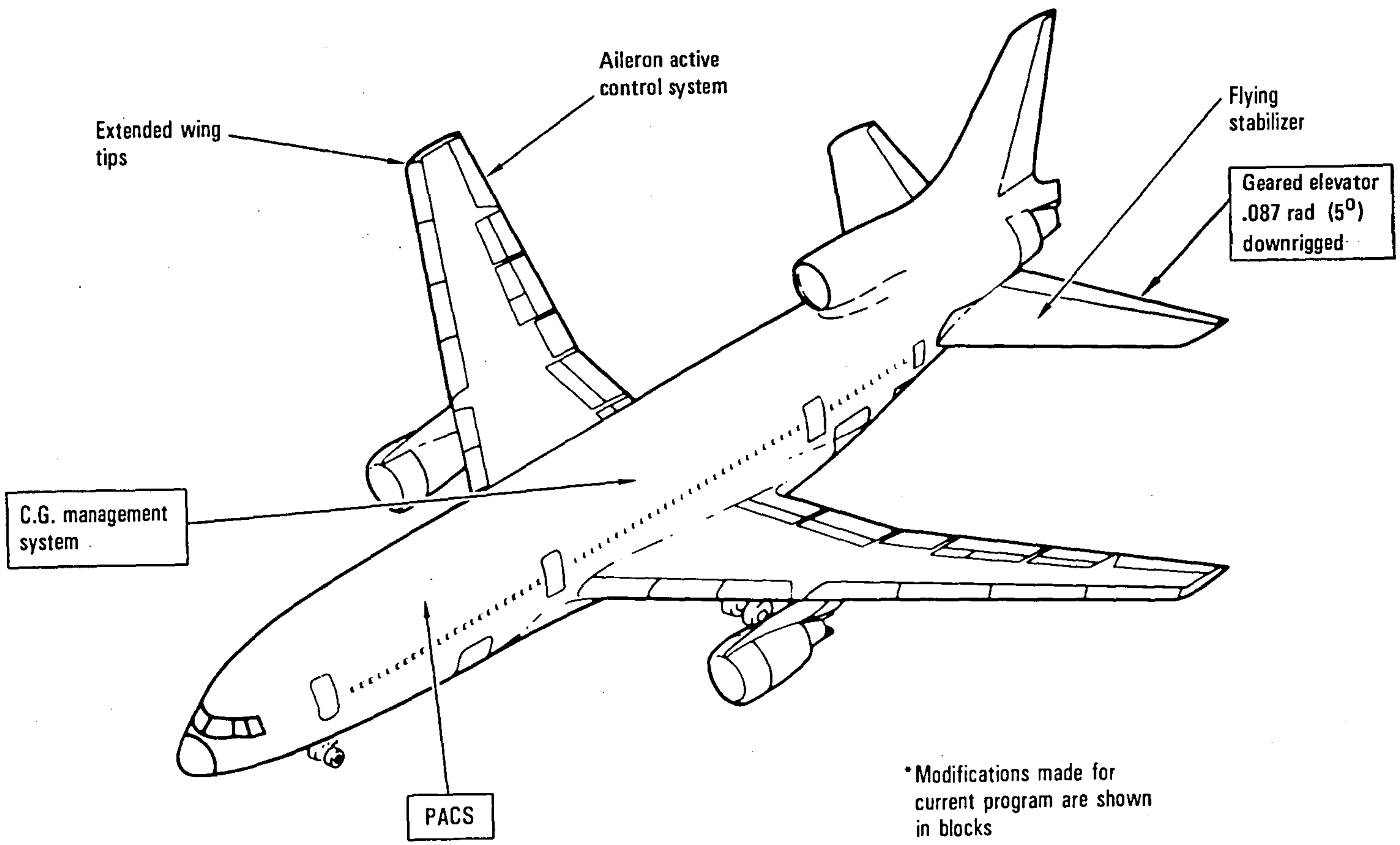

Figure 2. - Flight test airplane (L-1011 S/N 1001).

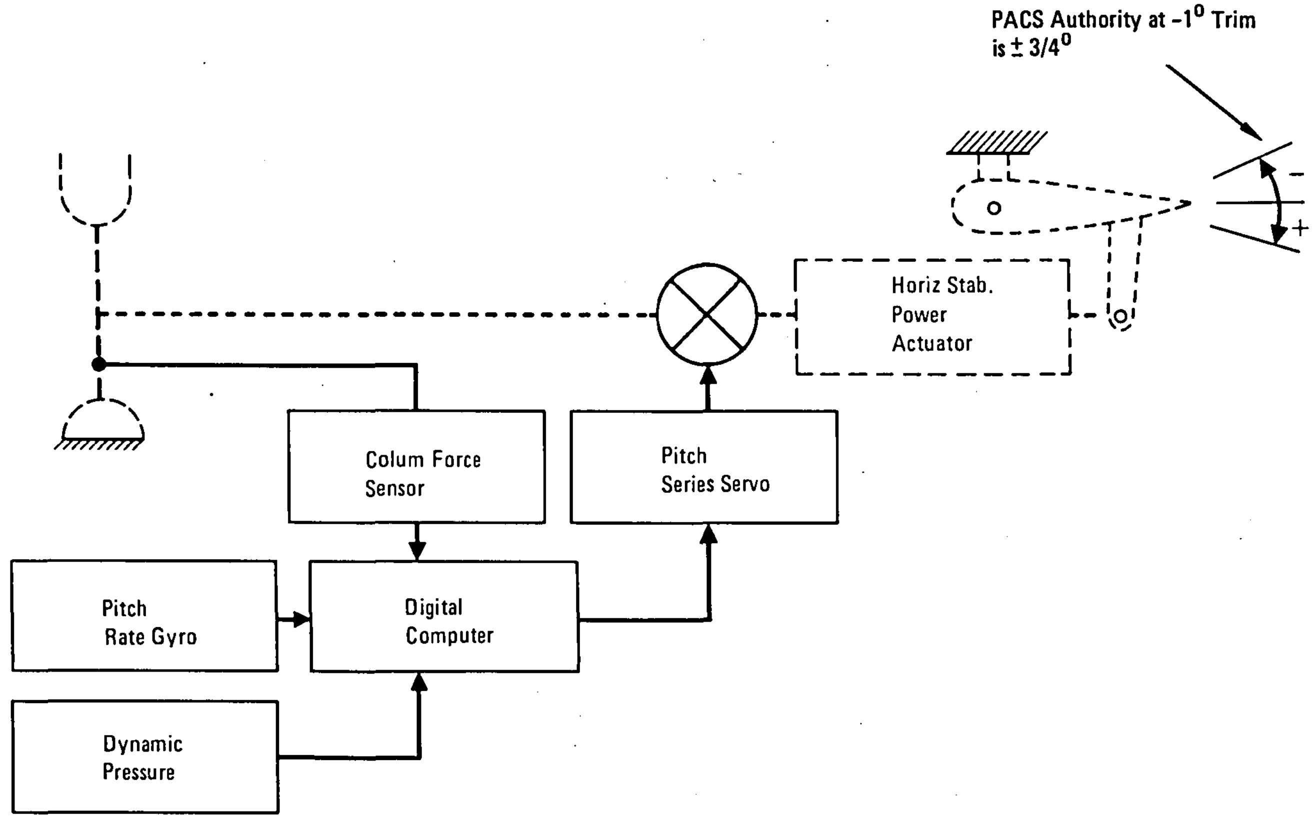

Figure 3. - Longitudinal control system with PACS.

2.2.2 PACS architecture. - The architecture of the PACS is shown in figure 4. The two dual-channel computers are modified Collins ACC-201 digital computers. The column-minus-trim (C-T) signals from the force sensors have a quadruplex arrangement so that a separate signal is sent to each computer channel. The pitch rate (PR) and dynamic pressure (Q_c) sensors have a triplex arrangement that provides separate signals to the A channels and a shared signal to the B channels.

The series servo is a National Water Lift 3010000 servomechanism which has an active/standby channel arrangement. Computer 1 provides control signals to the active channel and Computer 2 provides control signals to the standby channel. The dashed lines between the series servo and the computer in figure 4 represent servo output position feedback signals.

Figure 5 shows the avionics test pallet with PACS computers and associated equipment installed in the flight test aircraft. PACS computers are the block boxes installed in the near lower part of the pallet. The pallet also contains computer wiring intercept capability, magnetic core memories for PACS program storage, and a Digital Equipment Corporation PDP-11 terminal for interfacing with the transfer busses of each PACS computer.

2.3 C.G. Management System

The c.g. management system consisted of fixed ballast (lead and water) and a transferable water ballast system as shown in figure 6. The transferable water ballast system was installed in the forward and center cargo compartments of the aircraft as shown in the figure.

Figure 7 shows the c.g. envelope of the aircraft. A typical example of c.g. management is shown in the figure. Starting with the operation empty weight (OEW), the fixed lead ballast is added. Then, the fixed water ballast and transferable water are added to provide the zero fuel weight (ZFW). The remainder of the cycle shows addition of fuel, transfer of water to the aft tanks, fuel burned, and transfer of water to the forward tanks. For handling quality tests the c.g. limits were maintained between 25 and 39 percent mac.

2.4 Downrigged Elevator

The elevator was downrigged 0.087 rad (5 deg) to provide the required nose down control authority for aft c.g. flight conditions.

Each elevator on the L-1011 is independently connected by a mechanical system to the horizontal stabilizer as shown in figure 8. This system consists of a drive cable, return cable, quadrant (unsymmetrical cam), and an elevator push rod. The drive and return cables are attached to the fuselage structure at one end and the quadrant at the other end. Consequently, as the flying stabilizer is rotated over the range of +0.017 rad (+1 deg) (trailing edge down) to 0.244 rad (-14 deg), the unsymmetrical cam action of the quadrant moves the elevator push rod to rotate the elevator as shown in figure 9 for the standard and downrigged elevator configurations.

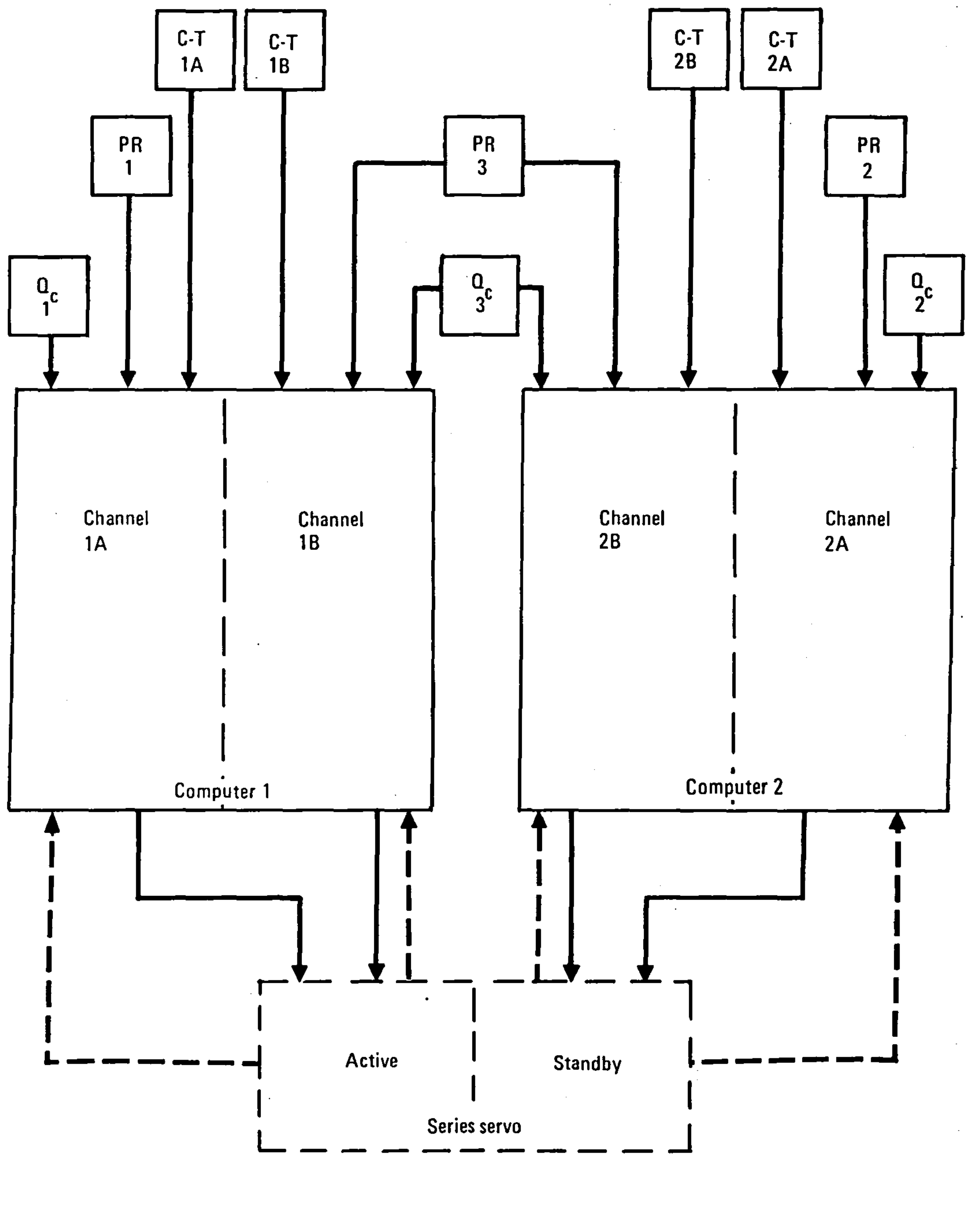

Figure 4. - PACS avionics system architecture.

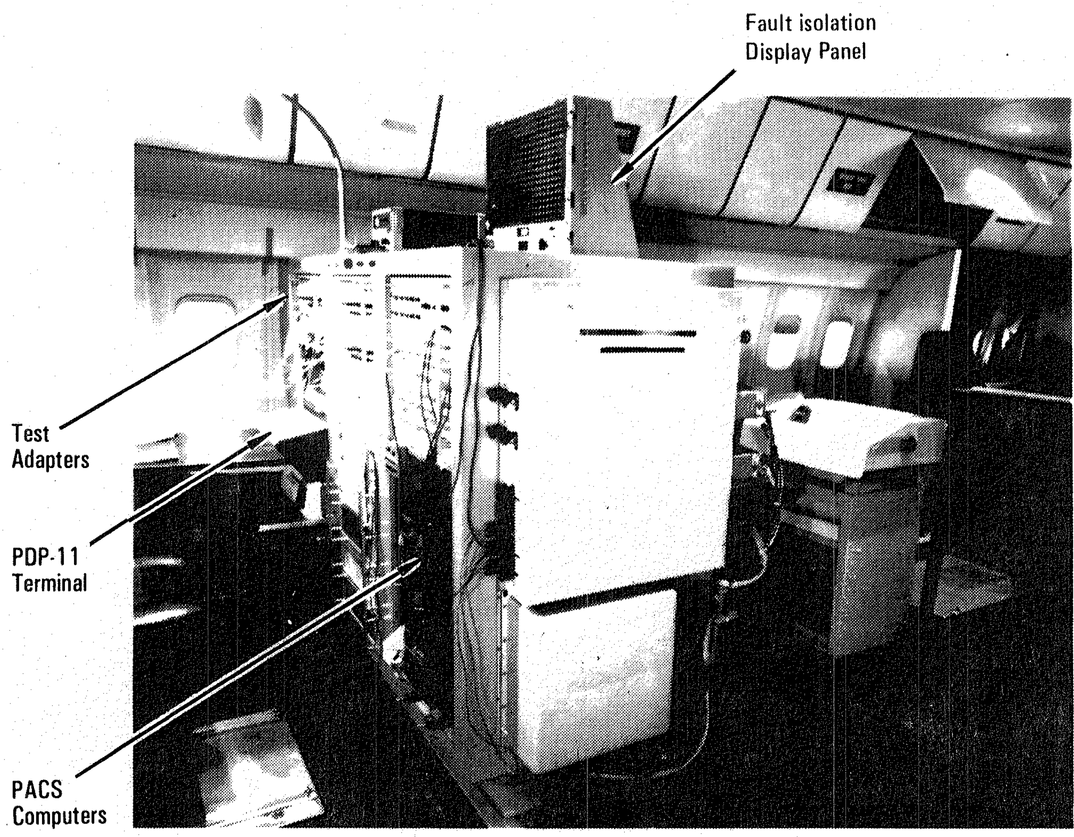

Figure 5. - PACS pallet installation in aircraft s/n 1001.

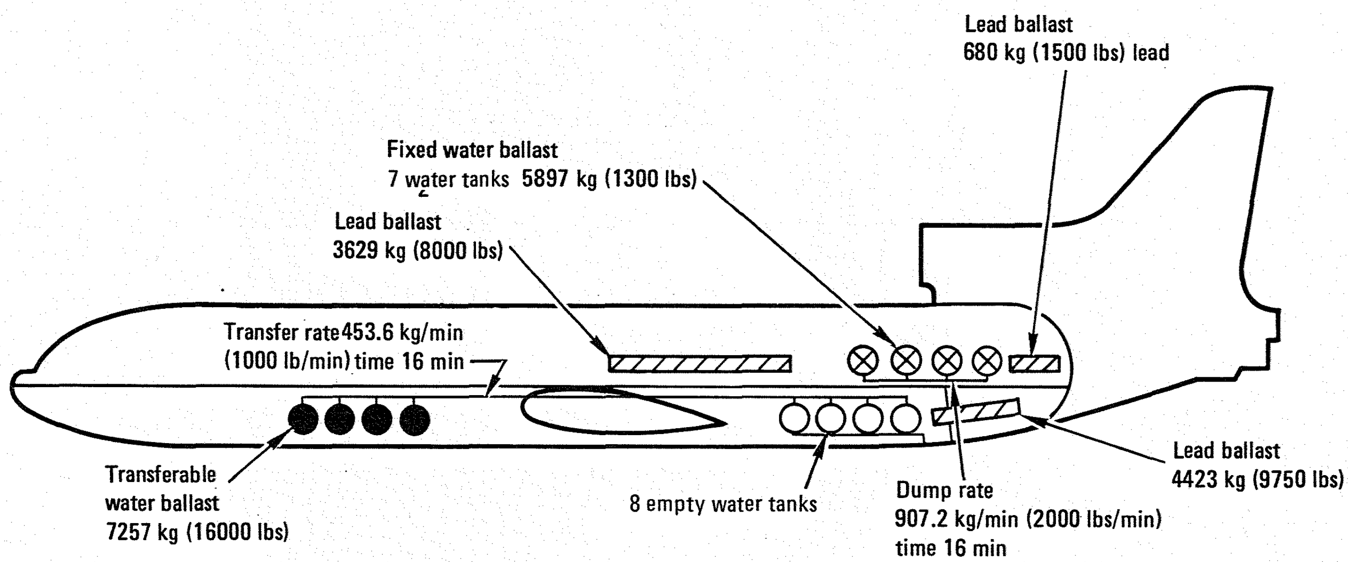

Figure 6. C.G. Management System

Figure 6. - C.G. management system.

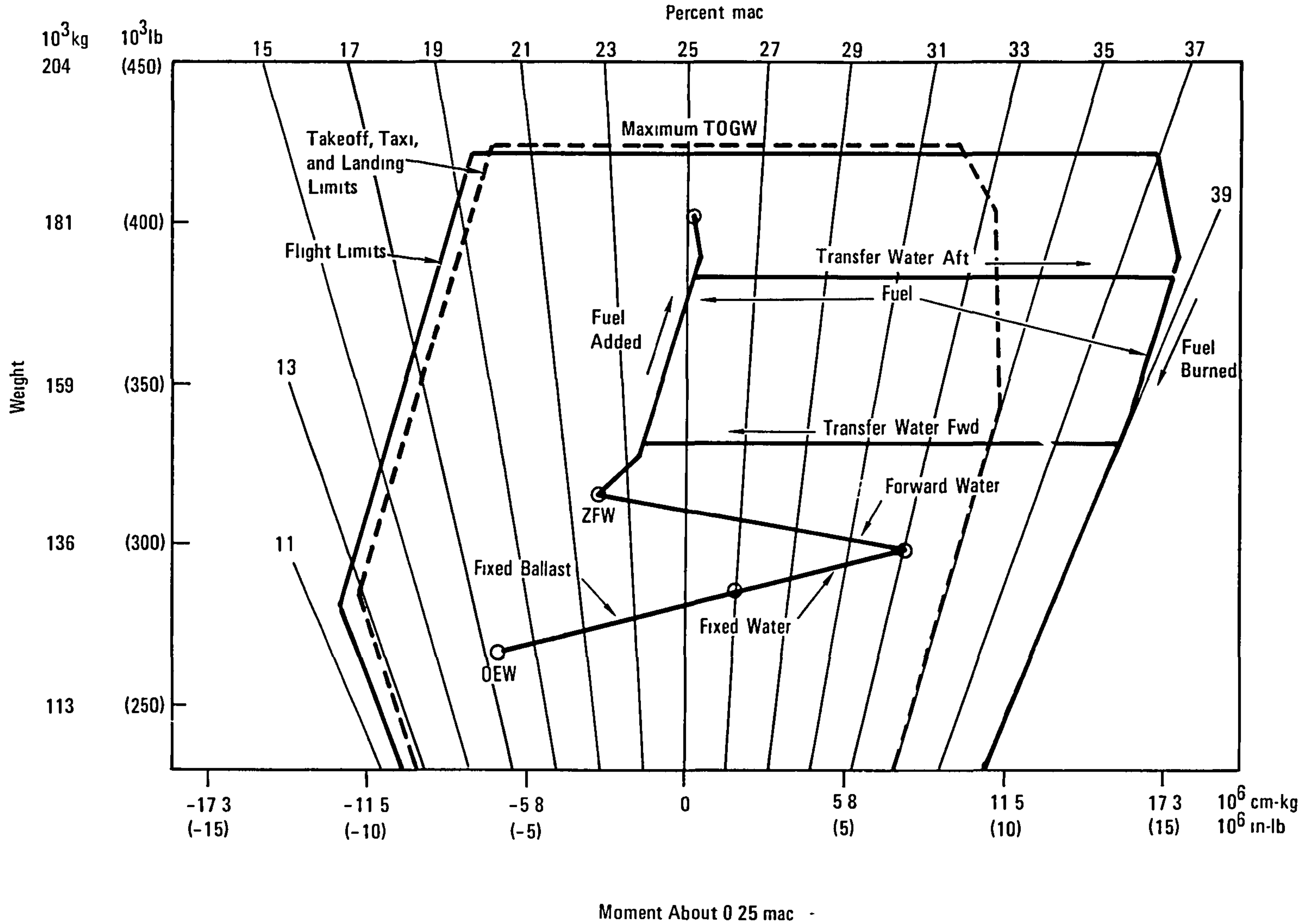

Figure 7. - C.G. envelope.

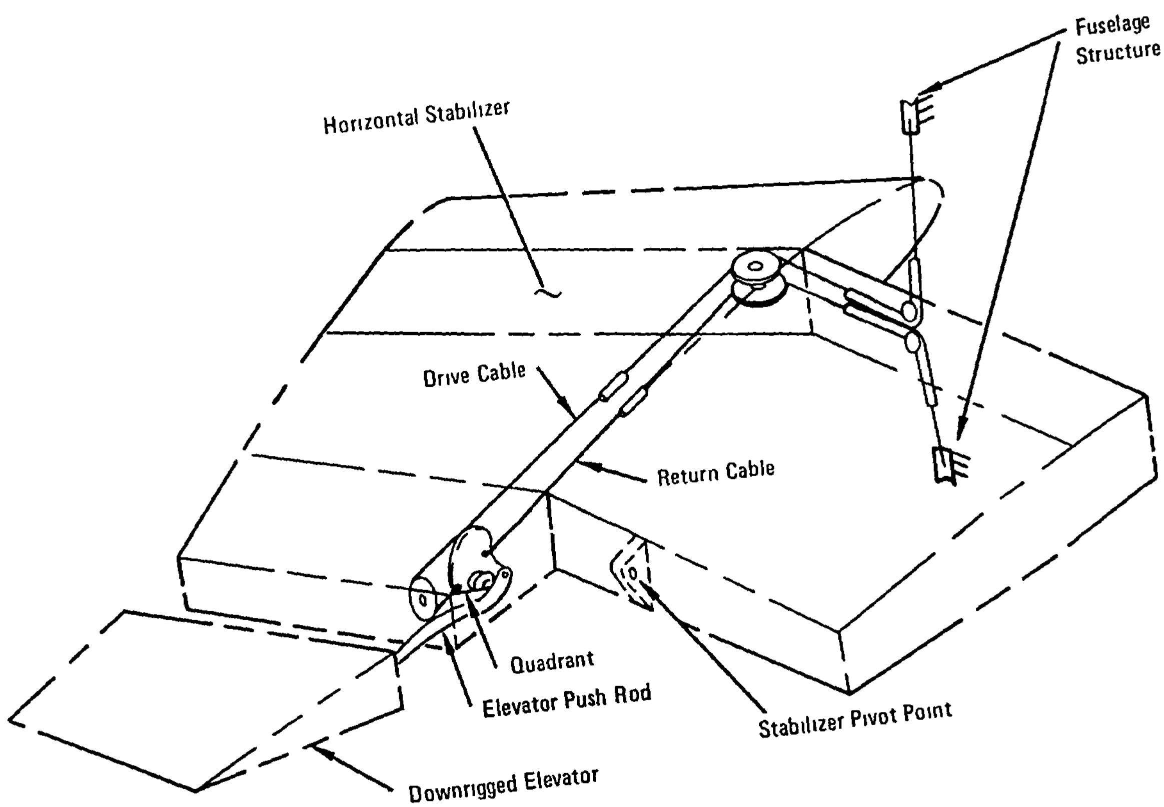

Figure 8. - Elevator control drive system (ELCON 11, left side).

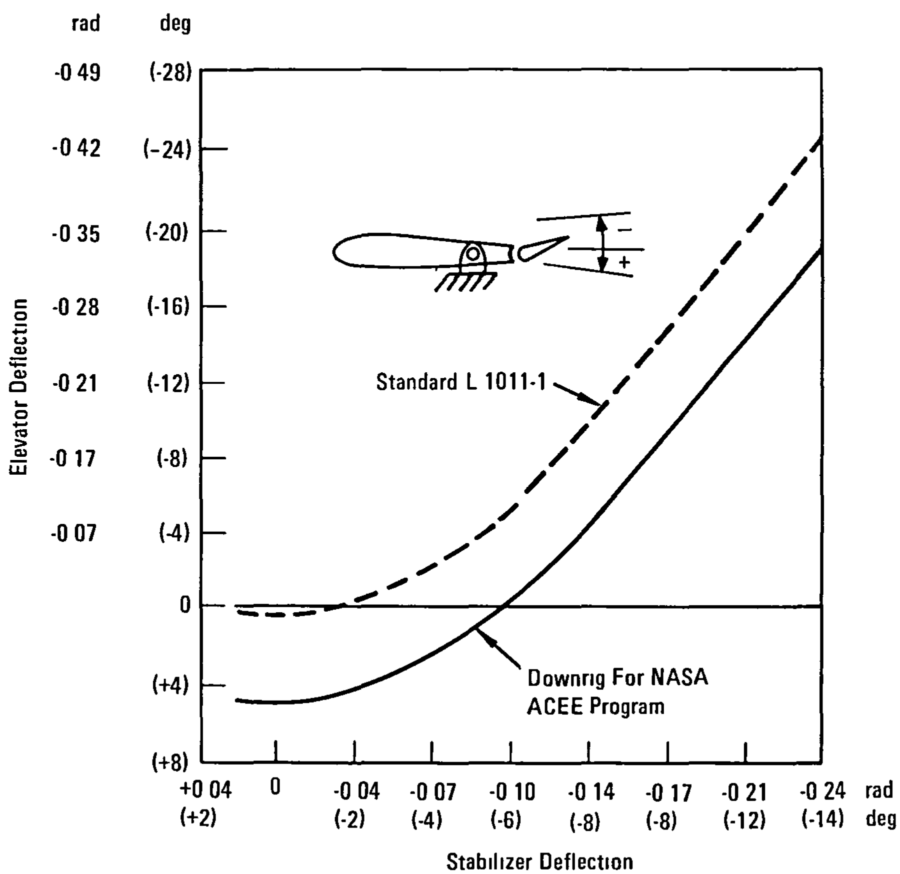

Figure 9. - Stabilizer/elevator gearing.

3. PACS FLIGHT TEST RESULTS

Eight dedicated flying qualities flights were flown by three Lockheed Engineering Flight Test pilots to evaluate the PACS. The test aircraft was ballasted to maintain 25 percent mac c.g. throughout the first flying qualities flight. During subsequent flights, the c.g. was moved progressively aft to a maximum of 39 percent mac.

The flight conditions evaluated are listed in table 1 and also shown graphically in figure 10. The majority of testing was conducted at four representative conditions: low altitude cruise (condition 10), high altitude cruise (condition 15), maximum normal operating speed (condition 16), and landing approach (condition 18). Specific tests included windup turns to evaluate maneuvering stability and control pulses to evaluate dynamic stability. PACS effects on trimmability, flight in turbulence and the landing approach control task were evaluated qualitatively.

Three different PACS configurations were implemented in the test aircraft and were selected individually in flight for evaluation. The first PACS configuration provided only pitch rate damping. The second configuration combined pitch rate damping with a feed-forward command to counteract some of the increased maneuvering force generated by pitch rate damping. The third configuration combined pitch rate damping with a washed-out feed-forward command to reduce the initial force to maneuver while retaining higher forces during long-term maneuvers. All three of these configurations were evaluated relative to the basic (PACS off) airplane.

The pilots judged PACS with pitch rate damping and feed-forward washed out to be the best overall configuration. Trimmability was greatly improved, maneuvering forces were increased and the maneuvering characteristics were substantially improved in regions of relaxed stability. The feed-forward portion of the system quickened the response of the basic airplane while the pitch damper provided good stability in turbulence and at relaxed static stability conditions. Both of these features tended to significantly reduce pilot workload at cruise flight conditions. The PACS was also found to reduce pilot workload in the landing approach, although not to the extend found in cruise.

TABLE 1. - FLIGHT CONDITIONS

Flight Condition	Speed	Altitude/(W/δ)
10 Cruise	M 83	0 64 x 10^6 kg (1 4 x 10^6 lb) W/δ
15 Cruise	M 83	0 73 x 10^6 kg (1 6 x 10^6 lb) W/δ
16 V_{MO}/M_{MO}	370 KCAS	7620 m (25,000 ft)
18 Landing (δ_F = 33)	1 3 V_S	Approach
20 Cruise	M 83	0 77 x 10^6 kg (1 7 x 10^6 lb) W/δ

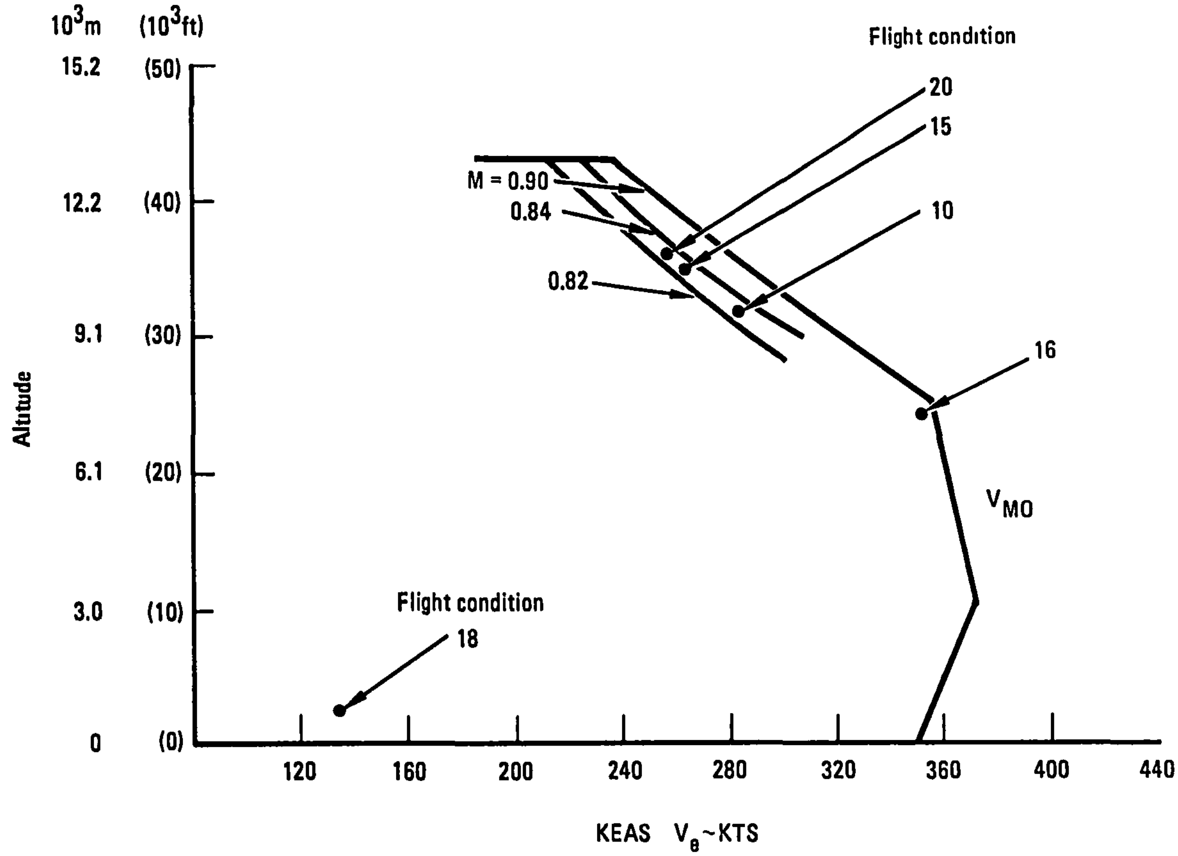

Figure 10. - Flight conditions.

Cooper-Harper pilot ratings for the preferred PACS configuration are compared to the basic (PACS-off) airplane for the cruise and high-speed conditions in figure 11. The figure shows that with PACS operating, flying qualities at 39 percent mac c.g. were rated as good as the basic airplane at 25 percent c.g.

4. CONCLUSIONS AND RECOMMENDATIONS

Analysis and test performed as part of previous programs indicate that c.g. management can be used to achieve 2 percent fuel savings for aircraft with current wing configurations and 4 percent fuel savings for aircraft with advanced technology wings. However, the c.g. must be moved aft which results in relaxed static stability margins and corresponding degradation of handling qualities.

This program has flight demonstrated a pitch active control system for a wide-body jet transport which allows a change in the static stability margin from +15 to +1 percent mac without degradation of the aircraft handling qualities within the linear stability region of the flight envelope. The technology can be applied to current-wing configuration aircraft to achieve the 2 percent fuel savings (based on flight test and wind tunnel data) provided that other control systems provide the necessary control for nonlinear stability conditions.

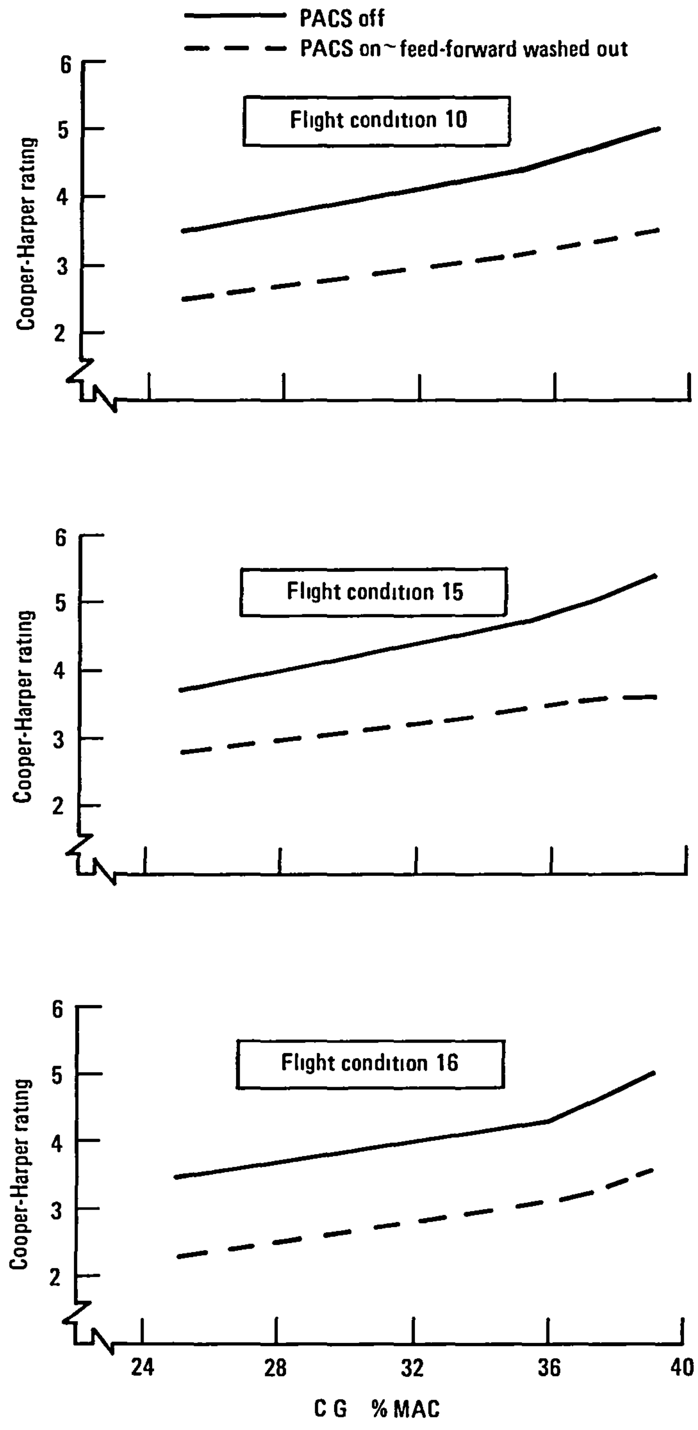

Figure 11. - Average pilot ratings, AACS on.

Subsequent steps to be taken in development of a PACS are to provide control for nonlinear stability conditions, for flight at negative static stability margins (e.g., to -10 percent mac), and for gust load alleviation. The 10 percent mac negative stability is required in order to achieve the 4 percent fuel savings for aircraft equipped with advanced wing configurations. Operation at the negative relaxed static stability margins require a high reliability PACS. Hardware failures must be extremely improbable for operation in adverse environments (e.g., lightning strikes) and for long periods of time under commercial airline operating conditions.

The path of technology development for a PACS that can be implemented on a future generation aircraft with advanced wing technology requires continued development and flight test of the advanced PACS along with a design and analysis study to provide the system architecture and component reliability necessary to make hazardous failures extremely improbable.

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16 Abstract

This report summarizes the development and flight test of a limited authority pitch active control system (PACS) on a wide body jet transport (L-1011) with a flying horizontal stabilizer. Two dual channel digital computers and the associated software provide command signals to a dual channel series servo which controls the stabilizer power actuators. Input sensor signals to the computer are pitch rate, column-trim position, and dynamic pressure. Control laws are given for the PACS and the system architecture is defined. Discussions are given regarding piloted flight simulation and vehicle system simulation tests that are performed to verify control laws and system operation prior to installation on the aircraft. Modifications to the basic aircraft included installation of the PACS, addition of a c.g. management system to provide a c.g. range from 25 to 39% mac, and downrigging of the geared elevator to provide the required nose down control authority for aft c.g. flight test conditions. Three pilots used the Cooper-Harper Rating Scale to judge flying qualities of the aircraft with PACS on and off. The handling qualities with the c.g. at 39% mac (+1% stability margin) and PACS operating were judged to be as good as the handling qualities with the c.g. at 25% mac (+15% stability margin) and PACS off.

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