ELECTRIC CONTROL LOADING - A LOW COST, HIGH PERFORMANCE ALTERNATIVE

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ABSTRACT

The simulation industry's conventional solution to the problem of providing flight control feel forces in a training device is based on hydraulic loading systems. The current state of the art in such control loading systems consists of a hydrostatic actuator controlled by a closed loop digital system. While the performance of these systems meets all training requirements, the cost of such systems remains high. Today's highly competitive simulation marketplace demands reduced costs. Considering current digital control loading systems, the hydraulic components (hydrostatic actuators, hydraulic plumbing, pumps, and valves) are a major recurring cost. Replacing these hydraulic components with an alternative active loading system has the possibility of significantly lowering recurring costs. In addition there has been an increasing trend in the industry to non-motion based specialty trainers, in which case a non-hydraulic solution is an advantage.

An electric motor based approach to the control loading problem is presented in this paper. Several systems using this approach have been developed to date, but have not exhibited the performance and fidelity to warrant consideration in most high fidelity training devices. The paper discusses an electric control loading system with performance that rivals current hydraulic systems. Particular emphasis is placed on the design considerations, the mechanics of the loader design, the electronics required, and the software algorithms developed. System performance is appraised against FAA PHASE II standards. The cost advantages and the applicability to various training devices is also examined.

INTRODUCTION

The correct static and dynamic simulation of the primary flight control feel characteristics is one of the most challenging and important aspects of the flight simulator. The pilot's ability to control the aircraft and his assessment of the aerodynamic handling qualities are largely predicated on the flight control feel. The experienced pilot has learned, perhaps subconsciously, to apply just the right amount of force to initiate and hold the spectrum of aerodynamic maneuvers. Since the human body is very sensitive to small changes in forces, an accurate and smooth simulation of the primary flight control feel is essential in a flight simulator.

Another important consideration revolves around the human being's capability to rapidly adapt to the sensed environment. This effect causes a pilot to quickly become "simulator conditioned"; he uses one technique on the simulator and another on the aircraft. The challenge of designing control loading systems for high fidelity devices with maximum transfer of training requires that the primary flight control feel forces provide the same tactile interface the pilot experiences in the aircraft. The flight controls must therefore replicate the static feel and dynamic characteristics of the aircraft to very tight tolerances.

The design of control loading systems has evolved significantly in the simulation industry's attempt to provide adequate flight control simulation. The original largely mechanical systems were gradually phased out by hydraulic systems with analog electronic simulation models. These systems, although able to meet simulation requirements, were limited by a lack of flexibility in modeling capabilities. The next generation of control loading systems consisted of hydraulic loaders with digital controllers and software based approaches to the flight controls modeling. These systems provide excellent simulation of the flight control feel without the drawbacks of the analog based approaches.

The loader used in the basic hydraulic systems has not changed much over the past decade. It remains as a high recurring and spares cost as well as a considerable maintenance expense. The replacement or elimination of the hydraulic components is an important step in control loading system development. Such a system can be described as an electric digital control loading system.The basic design goals of this system are:

- To provide the same or better force feel simulation capabilities as today's state of the art hydraulic control loading systems using an electric motor as the active loader.

- To make use of the same software and electronic capabilities which have been developed and are in use in today's digital control loading systems.

This paper presents the design of such a system from initial concept through the hardware design, system design, performance appraisals, and cost benefits.

DESIGN CONSIDERATIONS

The competitiveness of today's simulation marketplace exerts a great deal of pressure on both recurring and life cycle costs and on performance. Therefore a major design consideration in developing an electric control loading system is cost reduction. In fact this pressure was the driving force behind the IR&D project that developed this unique control loading approach.

The initial project step was the generation of system performance requirements. The specific response characteristics of the electric loader had to be defined. The important parameters considered were the maximum torque the loader needed to produce, the maximum acceleration and velocity requirements of the loader, and the overall frequency response needed to provide correct dynamics response characteristics.

Human factors studies [1] indicate that a pilot's maximum force capabilities at the primary flight controls of a fixed wing aircraft's control axes are as shown in Table 1. For rotary aircraft the applied force levels are typically lower. Based on these maximum levels and the typical mechanical advantages which exist in a simulator's linkage from the control to the loader, a maximum force output of 1000 lbs was specified as a design goal for the new electric loader.

AXIS	MAXIMUM FORCE (LBS)	MECHANICAL ADVANTAGE (TYPICAL)
Control column	200	4:1
Control wheel	150	5:1
Rudder pedals	300	2:1

Table 1 Typical channel loading requirements

Defining the maximum acceleration and velocity requirements was accomplished by analyzing a "worst case" velocity profile of a high performance aircraft's control movements. The velocity profile was obtained from a simulator loaded with a hydrostatic digital control loading system. The control was exercised at its maximum rate while recording velocity against time. Figure 1 depicts a worst case velocity profile.

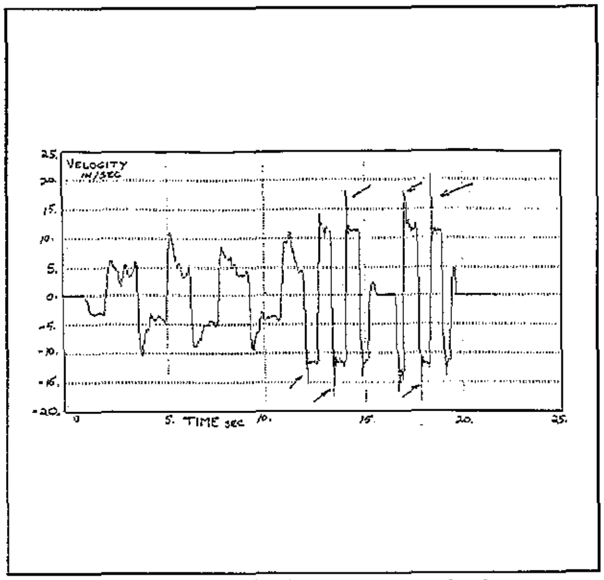

Figure 1 Worst case velocity profile of a high performance aircraft

Analyzing the response allowed the derivation of the maximum velocity and acceleration design goals for the new electric loader as shown in Table 2.

PARAMETER	MINIMUM REQUIREMENT AT LOADER
Velocity	5 in/sec
Acceleration	130 in/sec/sec
Force	1000 lbs
Frequency response	40 hz

Table 2 Minimum performance requirements for a high fidelity loader

The minimum frequency response performance required of the electric loader was derived from an estimate of the total system inertia and the time to move this inertia to maximum velocity. These performance requirements were used to properly size the electric motor and system bandwidth.

Other mechanical design considerations included the requirements for low friction in the linkage and loader bearings, low inertia of the loader and linkage, high side loading capabilities of the loader, and minimal to zero backlash or free-play. The standard loader package had to contain few custom manufactured parts and be easily adaptable to existing simulator or aircraft linkage.

Electronics design requirements demanded that the system have a high degree of noise immunity as well as a high bandwidth. The digital system had to close the control loop on force to provide a high fidelity of response to pilot input. The force loop approach minimizes phase error of the closed loop system and is the design basis of all modern control loading systems.

An overriding concern amongst all simulation customers is for trainee safety and the prevention of damage to the simulator's expensive cockpit equipment. The system had to contain both mechanical end of travel stops to protect from catastrophic electronic failures, and electrical limit switches for end-of- stroke detection. The electronics had to check for the "reasonableness" of the software servo command. There must also be a check for a computer valid or running signal. Finally, the safety system should remove active control from the loader in a smooth and non-abrupt manner.

The packaging of the system was the last major design consideration. The loader design had to be consistent with the packaging constraints imposed by a flight simulator base frame. The design goal for the physical volume of the electric loader was that it be no larger than existing hydraulic loaders. This would help make the electric control loading system viable for the upgrade of existing control loading systems as well as for new simulators. A standard package approach was desirable to allow rapid adaptation to various control channels and short engineering release cycles.

SYSTEM DESIGN

The muscle of the electric control loading system is the servomotor. The choice of a robust, high performance motor was critical. It was evident early in the design process that the robotics industry has made great strides in the evolution of electric servomotor technology. The requirements for ever faster and more precise automated machines has driven servomotor manufacturers to produce more sophisticated servo amplifier and torque motor combinations.

The current state of the art in the robotics industry is the AC servomotor. The AC servomotor offers several advantages over the more traditional DC servomotor. The armature of modern AC servomotor does not contain windings. It is made up of light weight rare earth permanent magnets. Since the DC servo motor armature does have windings, the AC servo motor has a performance advantage due to reduced rotor mass. The low inertia combined with high torque allows the AC servomotor to achieve fast acceleration and deceleration. In a similar sized package the AC servo motor will provide higher horsepower or alternatively the same horsepower in a smaller package than the DC servomotor.

A mechanical commutator in a DC motor switches current to the correct winding to keep the magnetic field rotating. The performance of the DC servomotor is limited by its ability to commutate this current at high speeds. The AC servomotor uses a three phase wound stator. The armature field is synchronized to the magnetic field through electronic commutation. This arrangement eliminates the commutator friction experienced by the DC servomotor and the wear of rubbing mechanical parts. Smooth performance is obtained at low speeds. The AC servomotor does not experience a limit in its ability to commutate providing high torque at maximum rated speeds. Since the AC servo motor was designed to be stiff near zero speed, a high degree of accuracy is obtained.

The combination of all these features: high torque with low inertia, full torque at rated speeds, smooth operation at low speeds, high accuracy, and no wearing mechanical parts, made the AC servomotor the best choice of an active element for the electric loader.

The ideal method of interconnecting the AC servomotor to the control linkage is a direct drive system. This offers the advantages of low loader inertia and minimal free-play while maintaining a high system bandwidth. However, the required force output of the electric loader makes a direct drive system impractical. The size of the motor would be prohibitive and inconsistent with a small volume packaging consideration.

Two alternative interconnecting approaches were considered, a ball screw and a gearbox. A precision ball screw has the advantages of low cost, short lead time, high reliability with proper lubrication, and high accuracy. The long linear stroke required to translate the rotary motion is a distinct disadvantage when considering packaging volume. The ball screw adds inertia, friction due to preload, and mechanical vibration noise due to the rubbing parts. Since a control loading system is basically a high gain force servo, any mechanical "noise" experienced by the load cell in the linkage will be amplified and result in a graininess of feel.

The gearbox approach offered several advantages over the ball screw. It does maintain a compact mechanical package, it can better handle side loads, has lower friction, and requires less lubrication and maintenance. The backlash present in a typical gearbox is a disadvantage. However, there are high precision gearboxes manufactured which exhibit little or no backlash. A high precision gearbox was selected for the electric system. It is integral to the motor shaft and is available off-the-self. The gearbox allows the servomotor torque and motion to be transmitted to the control linkage without noticeable free-play.

The addition of an output lever arm adapted to the common motor/gearbox shaft makes the standard loader package complete. This combination of elements has been sized to provide enough torque, acceleration, and velocity to exceed the previously determined requirements for a high fidelity system by a comfortable safety margin. The performance capabilities are summarized in Table 3.

PARAMETER	REQUIREMENT	CAPABILITY
Velocity	5 in/sec	21 in/sec
Acceleration	130 in/sec/sec	335 in/sec/sec
Force	1000 lbs	1335 lbs
Frequency response	40 hz	50 hz

Table 3 Electric control loader performance capabilities

The loader mechanical assembly is equipped with an over-torque safety slip clutch, a fixed mechanical stop, and over-travel proximity switches. The mechanical stop places a physical limit on the travel of the output lever arm for safety purposes. The slip clutch is installed between the lever arm and the motor such that contact with the mechanical stop or any obstacle will allow the motor to turn while the lever arm remains fixed. This feature is particularly important if the motor were to experience a run away condition. Normally before contact with the mechanical stop, the proximity limit travel switches will detect an over-travel, shutting down and stopping the motor. The system is fail safe, being protected by both electrical and mechanical systems. The overall simplicity of this design makes it easy to manufacture and mechanically compact. Figure 2 depicts the motor loader mechanical assembly.

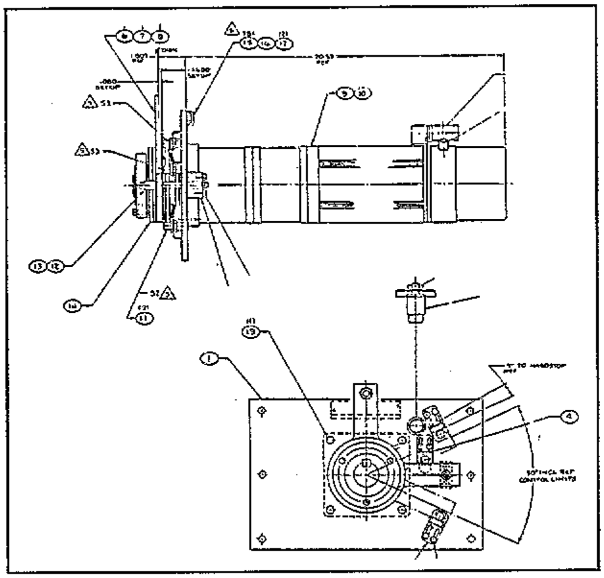

Figure 2 Electric loader mechanical assembly

The electric control loader is equipped with transducers to provide the necessary interface with the control loading software algorithms. Directly attached to the motor shaft are a tachometer for velocity measurement and an encoder for position information. A load cell for force measurement is installed in the control linkage to the motor. All these transducers are sized for correct operation over the full torque and speed range.

The electronics used to interface the digital control laws to the loader are substantially the same as for hydraulic based digital systems. The cardfile, microprocessor, host communications card, and servo drive I/O card are all common to both systems. The preamp assembly has been simplified by the elimination of the position demodulation circuitry. The electronic assemblies unique to the electric control loading system are the motor servo amplifiers, the three phase power supply, and the system safety card. Figure 3 depicts the system block diagram.

Each servomotor is driven by a servo amplifier which provides the necessary current and performs the electric commutation of the magnetic field. The servo amplifier is divorced from its robotics heritage by a plug-in personality module which customizes it for the electric control loading application. The personality module contains the servo dynamics loop compensation and properly conditions the motor current drive. It allows the electric system to be controlled by the same electronics as a hydraulic system. Maximum commonality with the hydraulic system is achieved and flexibility is provided for low cost upgrades.

The system is modular: one servo amplifier, one preamp assembly, and one drive I/O card are required per channel. All other cards are system level components and only one of each is necessary per cardfile. One three phase power supply can support up to six channels. The servo amplifier, motor, gearbox, transducers, power supply, card file, and microprocessor are all commercially available off-the-self components.

The system safety application card is unique to the electric control loading system and provides fail safe control. The nature of the safety features required for an electric system make this card unique. It removes electric power from the servomotor and shunts the motor current to ground forcing the motor to stop itself. This design feature eliminates the chance of the motor "coasting" to a stop upon loss of power. The system safety card also provides the software with an interface to the encoder. The traditional hydraulic system requirement for a LVDT or Temposonic interface is eliminated.

Very little unique software was developed for the electric control loading system. Over 90% of the existing software originally developed for the hydraulic system remains applicable to the electric system. All the physical models such as forward masses, aft quadrants, cable linkages, hydraulic actuators/boosters, generalized linkages, surface masses, and aerodynamic hinge moments are used unchanged. The models include parametric simulations of forward and aft friction, spring feel, forward and aft stops,

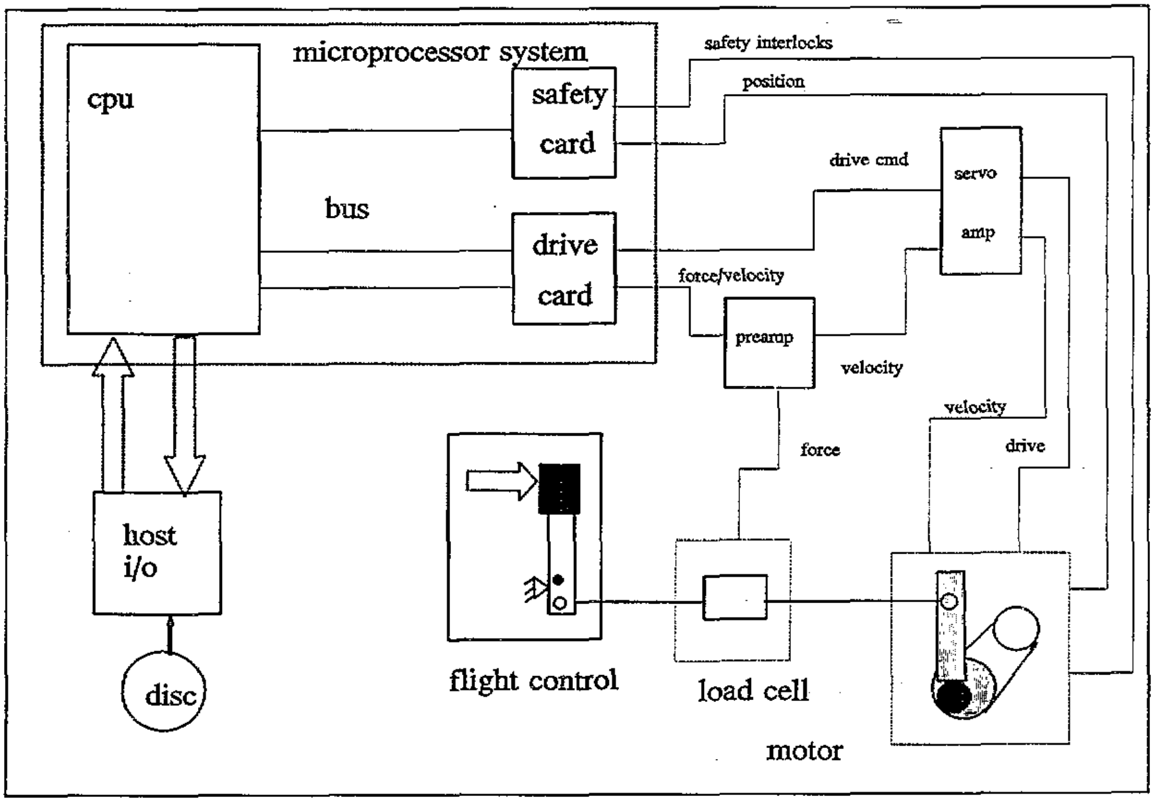

Figure 3 Single channel block diagram

non-linear gradients, preloads, cable stretch, inertia effects, and viscous damping. Since the microprocessor and cardfile are identical for both approaches the device interface, the interrupt handler, the real time clock control, and other executive software functions remain the same as well.

The unique software developed has two purposes. The first is to correctly interface the position encoder. The other is to provide a self-alignment position calibration mode on start up. The initialization mode slowly cycles the controls to one limit switch then back to the other limit switch returning to neutral. This cycle allows the software to "calibrate" the position by recording the exact end-of-stroke encoder positions, thereby defining the position scaling to the software models. In the hydraulic based approaches this procedure requires electronic alignment, and the adjustment is subject to drift over time.

The maintenance software utilities such as daily operational readiness check, built in test, and tuning/auto-calibration are based on the hydraulic system beginnings but were modified to handle any unique electric system interfaces.

PERFORMANCE APPRAISAL

The prototype electric control loading system has been extensively tested and refined in a laboratory environment on a test fixture. A cockpit procedures trainer for a British Aerospace 146 aircraft was used as a test-bed for the first production electric control loading system. The system exhibits smooth handling qualities with a wide dynamic range. The controls can be varied from the light responsiveness of a rotary wing aircraft to the heavier damped response of a large fixed wing aircraft. The simulation of hard stops, varied spring rates, friction, and preloads are equivalent in fidelity to a state of the art hydraulic loading system.

Testing has been performed to FAA Level C (Phase II) standards [5] and the electric system has proved as capable as the hydraulic systems. Figure 4 demonstrates a comparison of the electric and hydraulic systems' performance for a British Aerospace 146 roll control channel.

The performance of the safety systems is as planned. When a failure is detected, the controls turn off in a safe and elegant manner. There are no discontinuities associated with the safety system activation. The turn on/off characteristics are superior to the hydraulic systems for smoothness and acceptability.

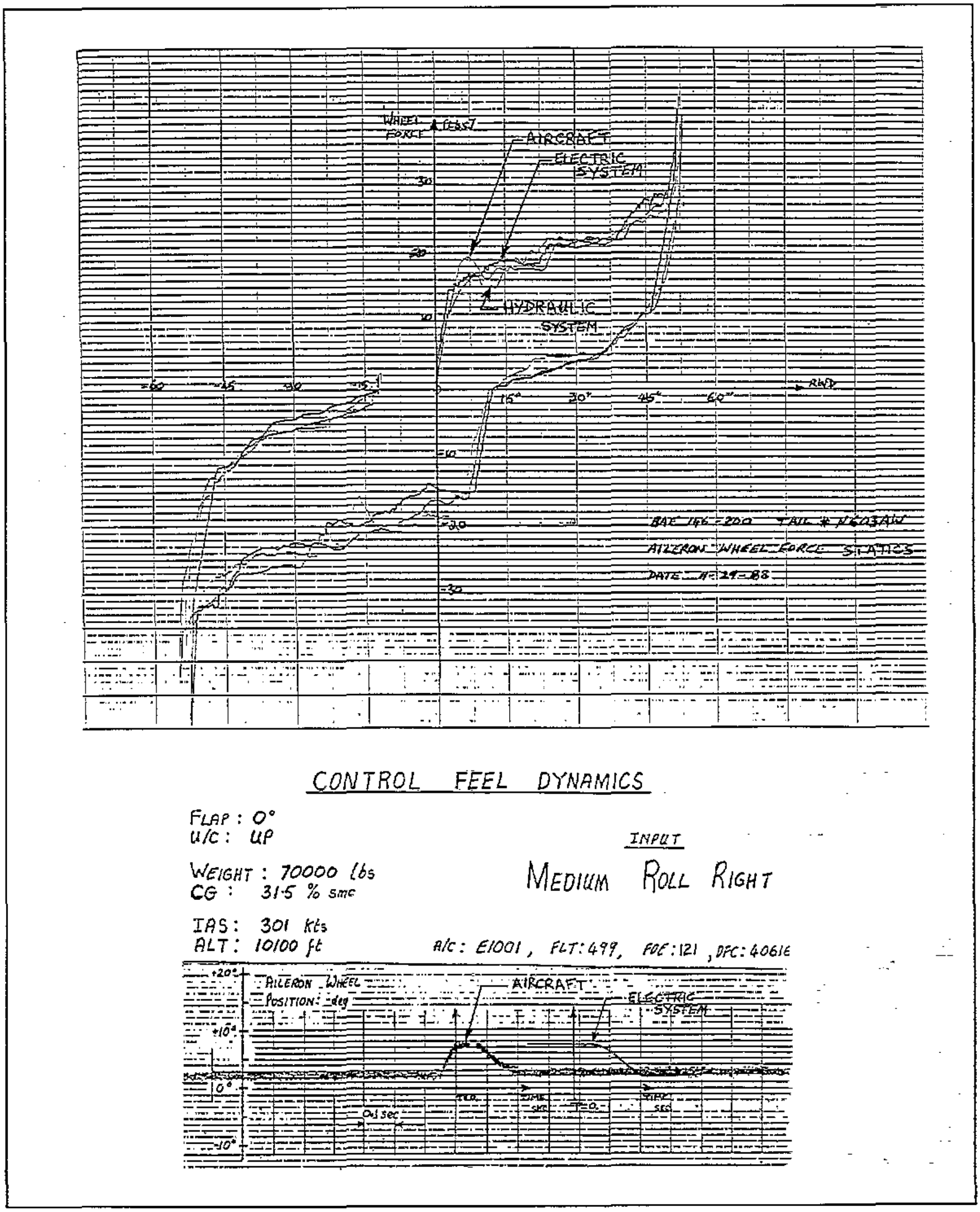

Figure 4 Electric/Hydraulic performance comparison

The stability of the electric system over wide temperature variations and over time has proved advantageous. The system does not exhibit drift common to many hydraulic systems. The electric control loading system is easily installed and requires less time to tune and make operational. It does not require the varied knowledge base involved with a hydraulic system. Technicians and maintenance personnel do not need any hydraulic training or background.

COST ANALYSIS AND BENEFITS

The electric control loading system is applicable to a wide range of devices. It has an advantage over hydraulic systems in a new class of training devices emerging on the marketplace. These devices are fixed base simulators which function as either cockpit procedures trainers or as high fidelity mission rehearsal devices. The lack of a motion system and the use of electric control loading eliminates the need for a hydraulic pump and the associated plumbing. This allows for a quick disconnect electrical facility interface enhancing the portability and mobility of the devices. The lack of hydraulics removes the potential danger of a hydraulic supply line break and prevents environmentally damaging hydraulic oil leaks.

The electric system is also applicable to full flight motion based simulators. The elimination of the plumbing to the base frame saves material costs and installation labor costs. The absence of a control loading hydraulic pump saves cost on the hydraulic power unit. The need for hydraulic flushing, hydraulic power unit adjustments, and servo valve performance tuning have been eliminated. The electric system has its servo performance determined by the preconfigured plug-in personality module. A comparative cost analysis appears in Table 4. Estimates based on material costs, labor costs, design and test costs indicate that the electric system will provide a 25% savings over the traditional hydrostatic approach.

The electric system will also exhibit a lower life cycle cost. Hydraulic system life cycle costs are relatively high, in part due to the maintenance required to ensure the hydraulic oil remains very clean. This requires frequent oil samples, oil polishing, and filter changes. Additionally the hydraulic power units and the heat exchangers have maintenance requirements. The electric system eliminates these costs.

One potentially higher cost of the electric system is for electric power. Calculations indicate that this is not the case. The electric system is not a large power user under the normal training scenarios. The servomotor was sized to deliver maximum load. Normal training use of the controls rarely demands maximum load. The servomotors duty cycle is low, which limits the average electric power for a typical training session to approximately 60 watts for a four channel system. This power level is easily covered by the power that would have been used by the hydraulic pump.

COMPONENT	APPLICABILITY Electric	Hydraulic	COST RELATIVE TO HYDRAULIC SYSTEM
Loader	Servomotor Gearbox Servo amps Power supply	Hydrostatic actuator Servovalve Transducers	Same
Cardfile	Drive I/O Safety card CPU Host I/O Status card Power supply Mech assembly	Drive I/O Safety card CPU Host I/O Status card Power supply Mech assembly	Same
Cabling	Required	Required	Same
Preamp	Load cell buffer Velocity buffer	Load cell buffer Velocity buffer Position demodulation	Lower
Hydraulic pump	Not required	Required	Lower
Hydraulic plumbing/valves	Not required	Required	Lower

Table 4 Electric control loading cost comparison

CONCLUSION

The electric control loading system was designed to provide high fidelity static and dynamic force feel simulation. Performance was verified by testing on a single axis test fixture and a three axis simulation device to FAA phase II standards. The feel forces simulation had a full dynamic range from light feel and quick dynamics to heavy feel and viscous response. The flight controls models were found to be fully capable and maintained a high degree of commonality with the hydraulic systems. The electronics assemblies also have a high degree of commonality. The electric loader has ample force, velocity, and acceleration capacities and has comprehensive fail safe features designed in. The safety system was found to fully protect the user.

While providing high performance, the electric system was found to have many cost advantages over the hydraulic based systems. These advantages include:

- Lower material costs
- Lower manufacturing costs
- Lower life cycle costs

The system was found to be applicable to several simulation markets including upgrades, non-motion based classroom devices, and full flight motion based devices.

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