NASA CONTRACTOR REPORT 166406

Benefits Assessment of Active Control Technology and Related Cockpit Technology for Aircraft

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Benefits Assessment of Active Control Technology and Related Cockpit Technology for Rotorcraft

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Prepared for
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1. SUMMARY

This report contains the results of studies of active control concepts and related cockpit concepts, and assessments of the benefits of these technologies for future civil rotorcraft. A review of the state-of-the-art in active control technology (ACT) and related cockpit technology (RCT) is presented.

In the broadest sense, active control may be defined as that body of technology applied to flight controls which results in improvements in vehicle performance and increased mission effectiveness. However, it is readily apparent that every conceivable control with a feedback loop could not be studied within the scope of this one man-year effort. The narrower focus of this work considered two main-rotor active control concepts, one of which incorporates multicyclic (or higher harmonic control - HHC) actuators located just below the swashplate, while the other concept provides for the actuators and power supplies to be located in the rotating frame. Each design concept is integrated with cockpit controllers and displays appropriate to the actuation concept in each case.

The benefits of applying the defined ACT/RCT concepts to rotorcraft are quantified by comparison to the baseline Bell Helicopter Textron Inc. (BHTI) Model 412 helicopter. These benefits include, in the case of one active control concept, (a) up to 91-percent reduction in 4/rev hub shears, (b) a flight safety failure rate of 1.96 x 10^{8} failures per flight-hour, (c) rotating controls/rotor hub drag reduction of 40 percent, (d) a 9-percent reduction in control system weight, and (e) vibratory deicing. Additionally, the related cockpit concept reduces pilot workload for critical mission segments as much as 178 percent visual and 25 percent manual.

NASA and FAA research options are discussed and recommendations are made that involve (a) major program to develop active control by means of actuators in the rotating frame and (b) a low-cost/risk noise-reduction program.

2. INTRODUCTION

Prior to 1960 helicopter engineers were beginning to consider seriously the benefits of active control. In specific areas, such as multiharmonic control, wind tunnel and even experimental testing was accomplished, but without terribly encouraging results. During the 1960s a few investigators persisted and during the 1970s their number grew to the point that the subject of active control for helicopters was a major topic of discussion in the technical community, as witnessed by the number of papers dealing with the subject at the 1980 National Forum of the American Helicopter Society.

While rotorcraft specialists were concentrating on model testing during the 1970s the fixed-wing industry was experimenting on a larger scale and with flight systems. This is not to say that rotorcraft technology has lagged in this field; rather, there exists a completely different set of problems. For instance, the fixed-wing control specialist does not have to deal with a control surface Mach number change of 0.4 in 0.075 second. And the accuracy demands are not comparable between the split surface redundancy of a fixed-wing application and a multiactuator (as many as six) swashplate mechanization for a helicopter.

Active control technology has been influenced greatly in the past few years by modern control theory, but it has been the rapid maturation of microelectronic technology that has made it possible to consider the economic application of active control to helicopters. The required speed and accuracy are now practical.

The program described in the following paragraphs attempts to quantify, within the scope of the effort, the benefits of the application of active control technology and related cockpit technology to rotorcraft.

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3. REVIEW OF CURRENT TECHNOLOGY

As a result of this effort a large number of documents were obtained, reviewed, catalogued, and filed within the BHTI Advanced Flight Controls Section. A list of these documents is contained in Appendix A. (This list contains some documents obtained under a prior IR&D task.)

Several other documents are referenced in the body of this report, especially those dealing with higher harmonic controls (HHC), or multicyclic control, and those dealing with related cockpit technology. These documents appear as regular references and/or they are synopsized in the following paragraphs.

3.1 ACTIVE CONTROL TECHNOLOGY

3.1.1 Previous Flight Control Programs

The state-of-the-art of flight controls was reviewed through a literature search. The results of previous flight control, cockpit display, and side-stick controller design projects were reviewed through a survey of the relevant open literature.

3.1.2 Automated Library Search

The second phase of the literature review consisted of a computer search of the data bases of several abstracting services. The areas of interest examined include the synthesis of digital flight control systems, the implementation of digital flight control systems, characteristics of integrated controllers, and strapdown inertial measurement systems. Of particular interest were those references documenting experience in software engineering and in the integration of software and hardware for flight programs. Following is the initial list of key words submitted during the computerized search:

Fly by Wire
Fly by Light
Heavy Lift Helicopter (HLH)
Tactical Aircraft Guidance Systems (TAGS)
Advanced Technology Components (ATC)
Side-Stick Controller
Sidearm Controller
Three-Axis Controller
Four-Axis Controller
Digital Flight Control System
Flight Control System Synthesis
Mission-Adaptive Control System
Aircraft Control Law Development

- Variable Stability Aircraft Control System
- Night/Adverse Weather
- Nap-of-the-Earth Controllability
- Terrain Following
- Strapdown Sensors
- Strapdown Gyroscopes
- Strapdown Accelerometers
- Strapdown Algorithms
- Strapdown Inertial Systems
- Strapdown Inertial Navigation Systems
- Attitude Heading Reference Systems
- Higher Harmonic Control
- Multicyclic Control

The data bases that have been accessed are

- Comprehensive Dissertation Index (CDI)
- COMPENDEX (Corresponds to the Engineering Index Monthly)
- Conference Papers Index
- INSPEC and INSP6976
- National Technical Information Service (NTIS)
- Society of Automotive Engineers (SAE)
- Defense Technical Information Center

These library search services provided the abstracts of documents listed by the service that are categorized by one or more of the requested key words. The abstracts were reviewed for topicality and the relevant reports acquired and reviewed.

3.1.3 Additional Sources

Additional documents have been suggested from other sources. These reports were reviewed for their applicability to this project.

BHTI is under contract [DAAJ01-76-D-0013 (P6C)] to the U.S. Army Aviation Research and Development Command (AVRADCOM) to evaluate and analyze foreign aerospace technical information. Documents relevant to any aspect of this project, including mission definition, were reviewed.

3.1.4 Current Control Technology (HHC)

This concentrated review clearly showed the accelerating pace of investigations related to this segment of active control technology. Table 3-1 shows the increasing activity by year.

3.1.4.1 HHC Review Synopses. Each of the investigations listed in Table 3-1 was thoroughly reviewed and an abbreviated synopsis prepared. The synopses of the more recent investigations are presented in Table 3-2.

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TABLE 3-1. ACCELERATING PACE OF MULTICYCLIC ROTOR CONTROL RESEARCH AND DEVELOPMENT

Year	Investigator(s)	Publication
1952	Stewart	ARC R&M 2997
1962	Drees and Wernicke	TRECOM TR-62-109
1966	Large Scale Aerodynamics Branch begins research	
1973	Kretz, Aubrun, and Larche	NASA CR 114693 and 114694
1974	McCloud and Kretz	NASA SP 352
	Sissingh and Donham	NASA SP 352
1975	McCloud	AHS Forum
1976	McHugh and Shaw	AHS Forum
1978	McCloud and Weisbrich	AHS Forum
1980	Brown and McCloud	AHS Forum
	Ham	AHS Forum, Vertica
	Hammond	AHS Forum
	McCloud	AHS Forum, Vertica
	Powers	NASA CR 159327
	Shaw and Albion	AHS Forum, Vertica
	Taylor, Farrar, and Miao	AHS Forum
	Taylor, Zwicke, Gold, and Miao	NASA CR 152377
	Wood and Powers	AHS Forum
	Wood, Powers, and Hammond	Vertica
	Yen	AHS Forum
1981	Abramson and Rogers	AHS Forum
	Molusis, Hammond, and Cline	AHS Forum

TABLE 3-2. HHC REVIEW SYNOPSES

Investigator	Publication	Year
KRETZ, AUBRUN, AND LARCHE	NASA CR 114693 & 114694	1973
MCCLOUD AND KRETZ	NASA SP 352	1974

- Wind tunnel test of jet flap rotor with higher harmonic pumping to yield multicyclic control
- Linear quasistatic representation - transfer matrix approach with a quadratic performance function
- T-matrix calculated open loop, applied to rotor
- Blade bending stresses reduced 50 percent or vertical shear reduced about 20 percent
- No discussion of power changes

SISSINGH AND DONHAM	NASA SP 352	1974

- Preliminary wind tunnel test of 4-bladed hingeless model rotor
- Did not directly sense quantities to be minimized: sensed flapping moment at 0.073R and thrust and algebraically created n/rev hub vertical shear, pitching moment, and rolling moment
- Transfer matrix calculated open loop, applied to rotor
- Derived hub moments and vertical shear reduced, with an increase in 4/rev blade bending moment
- No discussion of power changes
- Authors conclude that the technique is applicable only to low and medium advance ratios

TABLE 3-2. (Continued)

Investigator	Publication	Year
MCCLOUD	AHS FORUM PAPER	1975
	• Analytical study of multicyclic control effects on the Conformable Twist Rotor • Used Kaman CTR computer program to generate "test data" to be used in creating the T-matrix • Also determined collective and 1/rev cyclic controls, since the CTR is not deterministic • Used ROMULAN • Used weighting matrix to constrain control vector • When number of controls equals number of items to be controlled, can reduce controlled item amplitudes identically to zero (in theory) • In the analysis, successfully reduced vibratory hub shears to near zero while reducing blade bending moments by 50 percent	
MCHUGH AND SHAW	AHS FORUM PAPER	1976
	• Preliminary wind-tunnel test of hingeless rotor model (running off-design) • Used interpolation and extrapolation of results of arbitrary inputs to estimate (open loop) the appropriate higher harmonic controls • Able to reduce vertical hub shear, with slight improvement in blade loads and performance quantities	
MCCLOUD AND WEISBRICH	AHS FORUM	1978
	• Test of multicyclic rotor control on the Controllable Twist Rotor provided experimental data • ROMULAN and REGRESS used to analyze test data and provide appropriate higher harmonic control inputs	

TABLE 3-2. (Continued)

Investigator	Publication	Year
	• Examined weighting of various response characteristics	
	• Analysis of rotor response with the higher harmonic controls indicates either	
	• 25 percent reduction in flatwise bending moments with 83 percent reduction in control loads, or	
	• 50 percent reduction in flatwise bending moments with 30 percent to 60 percent reduction in control loads	
BROWN AND MCCLOUD	AHS FORUM	1980
	• Used CTR test from 1977 as source of data	
	• Used response weighting and control deflection penalty in linear quadratic regulator optimal controller	
	• Fixed-system accelerations at several points in airframe used in quadratic performance index	
	• Gain used to create suboptimal control with limited motion	
	• Successfully lowered the performance index	
	• T-matrix found to be strong function of μ, weak function of lift and propulsive force	
	• Real time identification of T-matrix most likely necessary	
HAM	AHS FORUM, VERTICA	1980
	• Wind tunnel tests of active controller designed to adjust each blade's feathering separately	
	• System designed to sense the response of each mode shape and control the motion	
	• Introduced interblade coupling in order to increase the flap damping	

TABLE 3-2. (Continued)

Investigator	Publication	Year
	• Experimental program demonstrated significant reduction in gust response - also will stabilize rotor motion in response to pitching and rolling motion of the aircraft • Vibration alleviation to be examined in future tests	
HAMMOND	AHS FORUM	1980
	• Wind tunnel test of an articulated rotor model • Kalman filter used • T-matrix and the vibration vector updated every rotor revolution • Used adaptive stochastic control feedback (with caution) to minimize a quadratic performance function • Also examined an adaptive deterministic controller and a constant gain controller, but no test results given • Convergence of control process dependent upon initial conditions • Measured vertical shear, pitching moment, and rolling moment at base of transmission • Significant reduction of vertical shear, some reduction of pitching moment, negligible reduction of rolling moment	
MCCLOUD	AHS FORUM, VERTICA	1980
	• Both papers are general reviews of the topic • Vertica paper discusses ROMULAN and shows that blade flatwise bending moment can be reduced • Vertica paper discusses "Control System Implications" • Safety	

TABLE 3-2. (Continued)

Investigator	Publication	Year
	• Fixed system control preferable to rotating system since the latter introduces the complexity of transmitting power and control signals into the rotating system	
POWERS	NASA CR 259327	1980
WOODS AND POWERS	AHS FORUM	1980
	• Design feasibility study of multicyclic control on OH-6A • Proposed analog 4/rev sine and cosine correlation instead of digital FFT for vibration identification. • Examined three actuator implementations - series integrated, swashplate link, combined primary and HHC • All three systems required at least 10 additional horsepower • Swashplate link chosen as optimal because of minimal aircraft modifications required - 39 pounds (1.5 percent gross weight) and 10.5 horsepower (4.2 percent of derated engine horsepower)	
SHAW AND ALBION	AHS FORUM, VERTICA	1980

	• Analysis, simulation, and wind tunnel tests
	• Analysis indicates
	  • Required pitch input essentially a linear function of uncontrolled harmonic response for unstalled flight
	  • Feedback controller fast enough to react to maneuvers and gusts would still be slow compared to harmonics to be controlled
	  • Required control varies greatly with airspeed and rate of climb	

TABLE 3-2. (Continued)

Investigator	Publication	Year
	· Findings supported by open-loop hingeless model rotor wind-tunnel tests · Controller design · Adaptive, closed-loop multivariable system · One-half second update time · Simulation showed the system to be stable even in the presence of large step changes in operating conditions · Closed-loop model rotor wind-tunnel tests gave · Fifty percent reduction in 4/rev hub vertical and pitching moment and 20 percent reduction in rolling moment at $\mu = 0.1$ · Ninety percent reduction in hub vertical shear and pitching and rolling moment at $\mu = 0.2$ · Negligible reduction in hub vertical shear and pitching moment, 80 percent reduction in rolling moment at $\mu = 0.3$ · Results at $\mu = 0.1$, 0.3 affected by saturating multicyclic control authority (1.5°) · Response time of 1.25 rotor revolutions · Maximum increase of 3.6 percent in shaft horsepower · Trim control inputs not affected · Oscillatory pitch link loads increased as much as 65 percent · Blade loads increased, but rpm variation showed this to be due to coalescence between modal frequency and n+1/rev excitation · Discusses advantages of three-bladed rotor for this application	

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TABLE 3-2. (Continued)

Investigator	Publication	Year
TAYLOR, FARRAR, AND MIAO,	AHS FORUM	1980
TAYLOR, ZWICKE, GOLD, AND MIAO	NASA CR 152377	1980

- Computer simulation of closed-loop adaptive controller for reduction of vibration at selected airframe locations
- T-matrix with quadratic stochastic performance index
- Both T-matrix and $\Delta\theta$ input updated once per rotor revolution
- Controller calculations performed in one-third rotor revolution
- Sensor location and relative weighting affects the vibration reduction
- There was approximately a 1- to 3- percent performance penalty for the particular case examined
- A noise-to-signal ratio of up to 15 percent did not degrade significantly the performance of the system

Investigator	Publication	Year
WOOD, POWERS, AND HAMMOND	VERTICA	1980

- Wind tunnel test of a four-bladed articulated rotor model
- Fixed-system loads measured at base of model
- Sweep of HHC inputs conducted and "optimal" controls determined (open loop)
  - Vertical shear reduced by 80 percent
  - Blade moments increased slightly (particularly torsional moment)
- Evaluated several n/rev control algorithms
  - Based on almost linear relationship between n/rev response and n/rev controls

TABLE 3-2. (Continued)

Investigator	Publication	Year
	• Single control input-single controlled output and multiple control input-multiple controlled output algorithms	
	• Not explicit T-matrix approach, but related	
	• Some aspects of proposed multicyclic control for an OH-6A discussed	
	• Measure loads in nonrotating mast, convert to digital signal	
	• Use an n/rev FFT to identify response	
YEN	AHS FORUM	1980
	• Analytical study of HHC application to a two-bladed teetering and four-bladed hingeless rotor	
	• Two-bladed teetering rotor	
	• Object to reduce the n/rev vertical hub shear (-) successful	
	• Increased rotor horsepower and inplane shears significantly, blade beam and chord bending moments somewhat, more than doubled n/rev pitch link load	
	• Four-bladed hingeless rotor	
	• Object was to reduce n/rev vertical hub shear and pitch-and-roll moments	
	• Eliminated each individually with single channel multicyclic control inputs	
	• Achieved complete nullification of n/rev vertical shear and 90 percent reduction in moments simultaneously	
	• Appropriate multiple control inputs were not a linear superposition of the single channel inputs, due to interharmonic coupling	

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TABLE 3-2. (Continued)

Investigator	Publication	Year
• Increase in horsepower of 2.7 percent, inplane shears lowered, blade bending moments, n-1, n, and n+1/rev pitch loads doubled		
ABRAMSON AND ROGERS	AHS FORUM	1981

• Analytical study of multicyclic control of a circulation controlled rotor
• Optimal control derived using method of feasible directions rather than the T-matrix
• Results verified using a CCR wind tunnel test
    • Significant compressor power reductions with a large increase in 2/rev blade loads
    • Can reduce 2/rev blade loads, but control signal is out-of-phase with the signal that reduces compressor power
• Further studies to be conducted
    • At different flight conditions
    • To include blade loads in the objective function (performance index)		

MOLUSIS, HAMMOND, AND CLINE	AHS FORUM	1981

• Analytical design of six separate controllers of various levels of sophistication
• Three adaptive controllers, three gain-scheduled controllers
• Virtues of adaptive controllers over gain-scheduled controllers
    • Do not need to measure flight conditions
    • Do not need to acquire and store large amounts of data for look-up and interpolation		

TABLE 3-2. (Concluded)

Investigator	Publication	Year
	• Potentially can achieve greater vibration reduction • Suggests combined adaptive/gain scheduled controller • Two adaptive and two gain scheduled controllers tested with a four-bladed articulated model rotor • The adaptive passive stochastic controller yielded better performance than the adaptive deterministic controller because of caution feature • Both adaptive controllers out-performed the gain-scheduled controllers, which saturated without providing vibration reductions • Found that closed-loop and open-loop T-matrices differed substantially • Could not reduce n/rev fixed-system vertical pitch and roll accelerations simultaneously	

3.1.4.2 HHC Review Conclusions. The general conclusion resulting from this effort is in agreement with Shaw and Albion (1980), "The technology is now ready for full development."

More specific conclusions are as follows:

a. The analytical and experimental work has shown that multicyclic rotor control can provide significant reductions in vibration with small penalties.

b. Adaptive controllers are superior to gain-scheduled, and those that include caution are superior to deterministic controllers.

c. Necessary system identification tasks can be performed, and control algorithms updated, in less than one rotor revolution.

d. Required control amplitudes are characteristically small.

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e. Rotor blades are being used to absorb part of vibration. Solutions that may reduce blade loads are

  (1) Tune away from n-1, n, and n+1/rev.

  (2) Account for increased loads.

  (3) Use state estimator to include selected blade loads in performance index for minimization.

f. Horsepower increases of 1 to 3 percent due to performance degradation are typical.

g. A gross weight increase of 1.5 percent can be anticipated because of additional equipment required.

h. A gross weight increase of 0.75 percent can be anticipated because of increased structural mass in the control system.

3.2 CURRENT RELATED COCKPIT TECHNOLOGY

This review includes data from selected literature, from previous studies conducted at BHTI, and from interviews with personnel directly involved with the civil missions for rotorcraft.

The literature review was confined essentially to studies within the past 10 years. For a comprehensive review of the literature, the reader is directed to the NASA study in Reference 1. This report will amplify some of the findings.

3.2.1 Controlled Configurations

Conventional controls include manually operated, direct-linkage displacement controls such as cyclic control of pitch and roll, right/left pedal controls, collective pitch control up/down, and throttle control. Conventional controls require a force applied to a long lever arm such that the pilot's action on the control stick directly moves the control surface through a long series of mechanically connected levers. Despite this requirement, some small side-arm controls have been efficiently and safely flown on production helicopters. An example is the side-arm controls for both cyclic and collective pitch in the gunner's compartment of the BHTI AH-1 series. A photograph of the side-arm cyclic may be seen in Figure 3-1.

With boost systems and the advent of fly-by-wire and fly-by-light systems that do not demand large force components, side-arm controls, hand controls, and even fingertip controls are becoming operational design realities. The configuration and dynamics of these controls for helicopters challenge the design engineer.

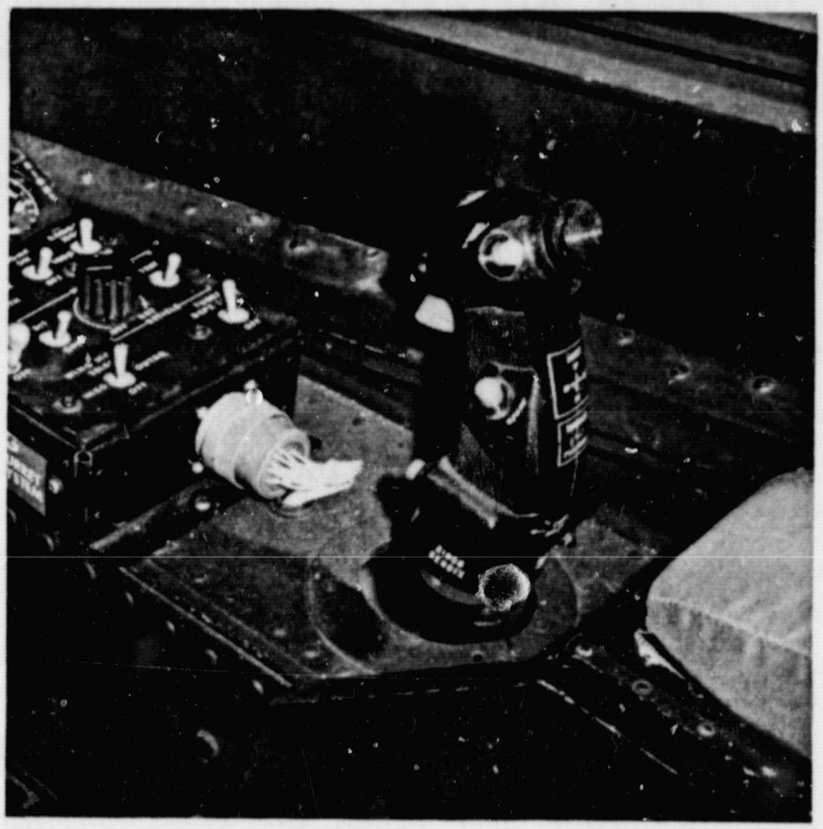


Figure 3-1. Conventional side-arm cyclic grip used in Bell AH-1 (Cobra) series.

In the early 1960s, BHTI designed and developed a fingertip control for a cyclic stick controller. Figure 3-2 shows this installation. The system permitted a variety of stabilization modes with this control, including altitude hold and attitude hold modes. It was successfully flown in a UH-1 helicopter under both VFR and simulated IFR conditions (Refs. 2 and 3).

BHTI studies have addressed a variety of primary controller configurations. One study examined the following four mocked-up helicopter combinations (Ref. 4):

a. Pump-handle collective

b. Dual-grip cyclic (panel and floor mounted), 2-axis

c. Side-arm cyclic

d. Dual-grip cyclic (panel and floor mounted), 3-axis (pitch/roll/collective)

Pilots were asked to conceptualize the use of the mocked-up controls for certain emergency conditions, as well as difficult and normal flight conditions. The conclusions favored the conventional controls, with the least favored being the dual-grip 3-axis controls.

An experimental 3-axis displacement side-arm controller developed at BHTI in 1980 was built and evaluated using a tethered model of a V/STOL. Pilots indicated they liked the feel and dynamics of this control. Photographs may be seen in Figure 3-3.

A 3-axis displacement controller has been developed and successfully flown at the Human Engineering Laboratory of the U.S. Army, Aberdeen, Md. This controller, mounted on top of the center cyclic stick, has been well-received in demonstrations; however, studies with this control seem to have ended.

A 3-axis force controller (pitch-roll-yaw) has been developed and successfully flown by Sikorsky Helicopter. They are currently conducting some lab studies that look at the effect of control accuracy using a 4-axis control operated by one hand while the other hand is performing other tasks.

Boeing-Vertol Company is also developing a multiaxis controller. For the ADOCS program (Advanced Digital/Optical Flight Control System) a 4-axis side-arm controller is proposed.

The above studies rely heavily on subjective evaluation of the controllers. The classic study by Knowles (Ref. 5) indicated that pilot acceptance of controls is not always reflective of the design that improves comfort, visibility, and fatigue. This

Figure 3-2. Fingertip controller for cyclic control functions.

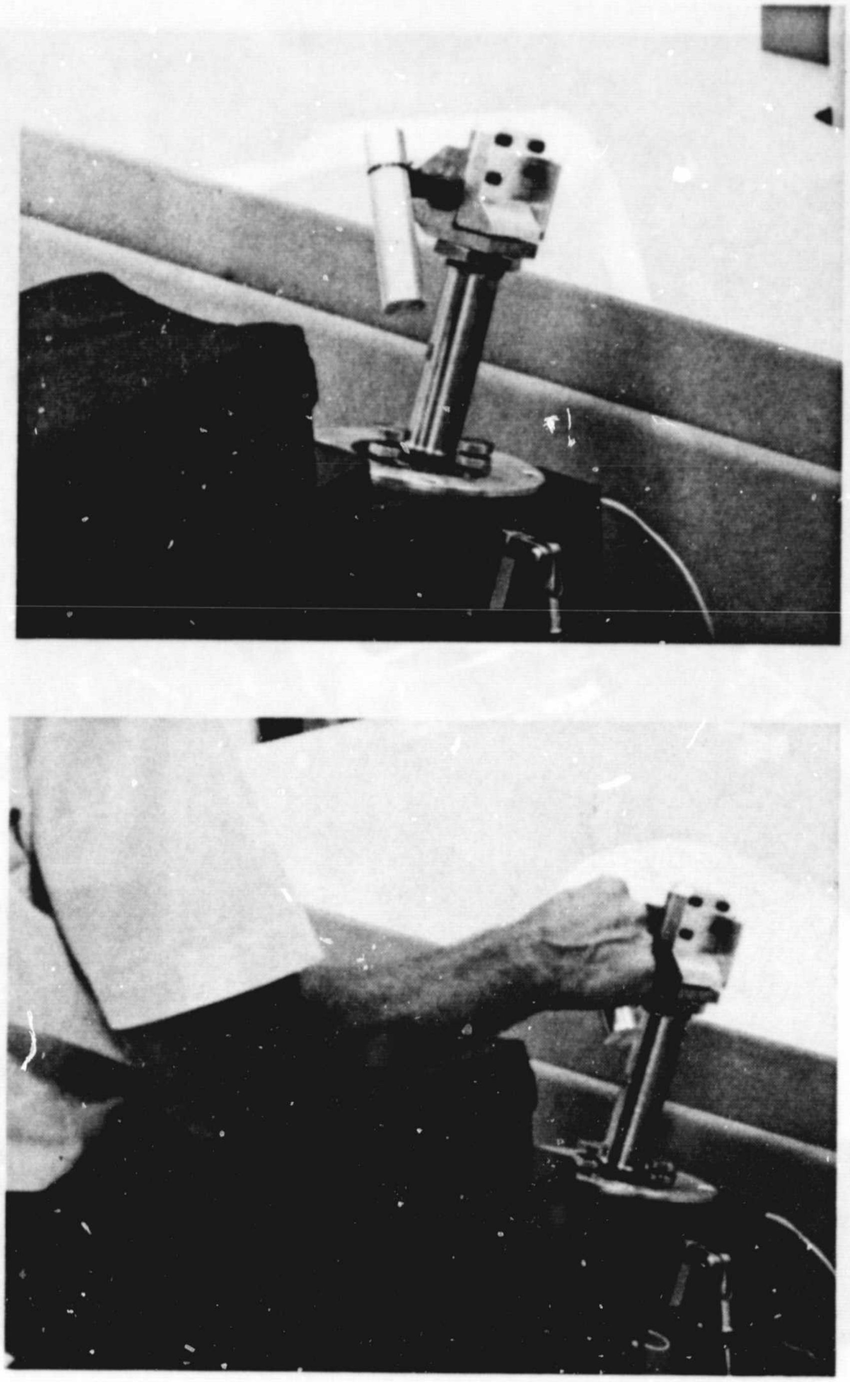


Figure 3-3. Three-axis displacement side-arm controller.

finding was reemphasized by a BHTI study for the helicopter case where it was found that "feel" was highly important to pilot acceptance, even outweighing performance ability. "When a pilot is asked to evaluate various controls in a mockup or simulated environment," the study concludes, "he has to depend on past training and experience to help him in his judgments. To a large extent, he must rely on the kinesthetic muscle senses that have been developed over the years. Thus, a control that is compatible with these kinesthetic movements will certainly feel more comfortable and familiar to the pilot, and it is more likely to be rated higher than a control that conflicts with these embedded muscle patterns."

Both of these researchers are suggesting that comprehensive simulator and operational objective testing, with objective data, be accomplished on any new control configuration.

3.2.2 Man/Machine Dynamics

In review of the man/machine dynamics, a classic human performance text (Ref. 6) reduces the data to the simple dichotomy: force and displacement controls. The advantages and disadvantages of these types of controls include the following:

a. Advantages of force controllers:

   (1) Better single-axis tracking, particularly at high frequencies.

   (2) No space required for control movement.

   (3) Returns to zero output when force is removed.

   (4) Less inadvertent input under vibration conditions if good forearm support is provided.

b. Disadvantages of force controllers:

   (1) A dead zone must be introduced in multiaxis tracking to prevent inadvertent cross coupling between axes.

   (2) Continuous force application is required to maintain a nonzero output with position controls system or when tracking very low frequency input signals. This may lead to undue fatigue during prolonged operation.

   (3) Difficulty in coordinating two or more controls to the same system.

c. Advantages for position controls:

   (1) No force is required for constant output.

   (2) Visual and kinesthetic feedbacks of control position are available.

d. Disadvantages for position controls:

   (1) More subject to inadvertent inputs from an operator.

   (2) No return to zero when released unless spring system is provided.

   (3) Do not provide clearly defined zero output.

   (4) Tracking error generally higher, especially with high-frequency inputs.

e. Some conclusions from the literature indicate the following:

   (1) Man operates as a position output device, more than a force output device.

   (2) Force controls are indicated to be superior when the control system has oscillatory position control dynamics.

   (3) Differences in control output become smaller between force and position controls with increasing natural frequency and with increasing damping of the control system.

An Air Force report (Ref. 7), describes the force side stick in an F-16 fighter aircraft. Force commands were used in both lateral and longitudinal axes. Comments showed a trend from oversensitivity of the aircraft to sluggishness as forces were increased. Pilots complained of excessive wrist bending with a 20° deflection of the control. They were unable to make precise corrections when the loss of stick motion was experienced while using a force-controller. Large control force gradients were preferred and, to a lesser degree, smaller control stick motions with heavier control force gradients. It is possible that this applies to fixed-wing fighter pilots and not the helicopter pilots. The best tracking performance was found to be when the conditions of light to moderate stick force gradients were combined with moderate stick motion.

4. CONCEPTUAL DESIGNS

The BHTI Model 412 helicopter served as the baseline rotorcraft for this task and throughout this contracted study. The selection of the baseline vehicle was not a part of the contracted effort; rather, it was a part of the contractor's original proposal. The newer BHTI Model 222 was not chosen because of technical limitations attributed to the two-bladed rotor in Reference 8, as far as the benefits of multicyclic rotor control are concerned. The discussion in Reference 8 of multicyclic rotor control applied to two-bladed rotors tends to explain or track the results of BHTI's earlier flight tests reported in Reference 9.

Emphasis is placed on active rotor controls and cockpit requirements compatible with the level of sophistication of the controls, yet technically commensurate with hypothetical production time frames in the late 1980s or early 1990s.

Of all possible candidate control concepts, only three were considered for this study: (a) the baseline BHTI Model 412 with multicyclic actuators in series with the hydraulic power boosts, (b) the baseline helicopter with fly-by-wire primary/multicyclic actuators, and (c) the baseline helicopter with FBW multicyclic actuators in the rotating system. The second candidate was eliminated because of excessive hydraulic flow requirements.

4.1 ACTIVE CONTROLS

4.1.1 Multicyclic Actuators in Series With the Primary Hydraulic Boosts

The components of this conceptual design consist of three single-piston actuators; electronic driving circuitry, including signal function generators; and nonredundant microprocessor capacity. The single-piston actuator, #41005470 Multicyclic Control Actuator, was predesigned specifically to meet the loads and frequency requirements of the Model 412 rotor. One of these actuators would be mounted directly on the output of the collective and cyclic hydraulic boost actuators, typically as shown in Figure 4-1. Design requirements for the Multicyclic Control Actuator are shown with the schematic in Figure 4-2. Basically, the actuator is intended to provide precise control up to 30 Hz, at amplitudes corresponding to ±2.4° of blade feathering on the Model 412 rotor.

The electronic control unit will accept command signals from external function generators and reproduce those functions in the form of an actuator stroke proportional to the command signal

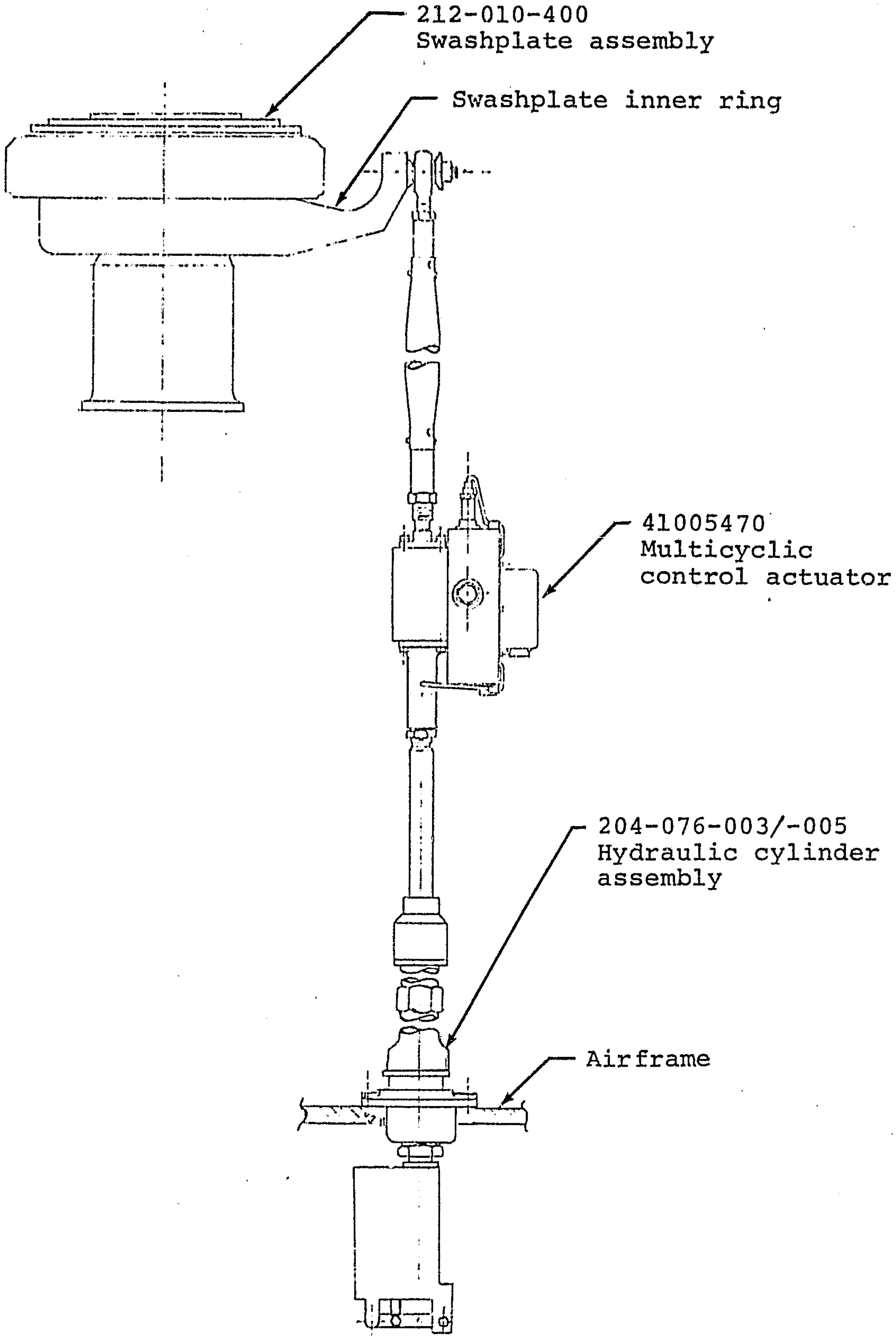
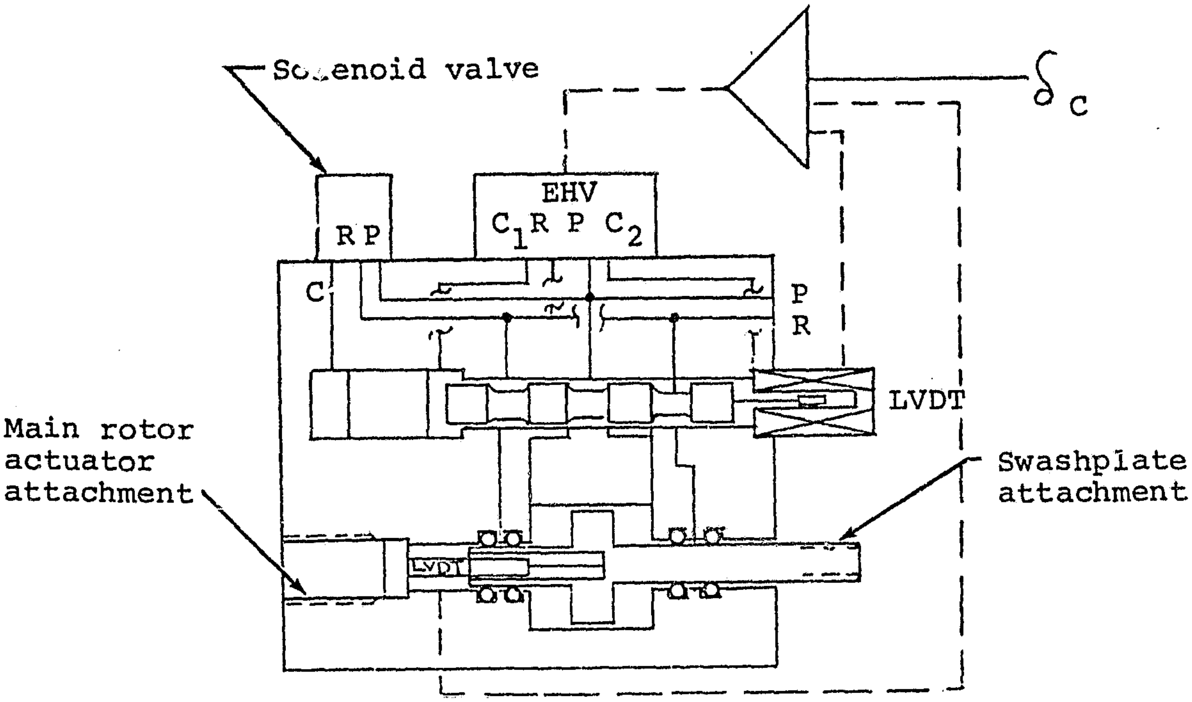


Figure 4-1. Multicyclic control actuator on the Model 412 helicopter.



Piston area	0.77 in^2
Stroke	0.60 in, total
Closed loop frequency response	$^{+2}_{-1}$ dB, 0 to 30 Hz

(Power off drives power stage to hydraulically power actuator to hard retract.)

Figure 4-2. Multicyclic control actuator schematic.

amplitude and direction. The signal scaling is +10 volts or -10 volts dc, peak-to-peak, yielding plus or minus a full stroke from center position. The bandwidth is 0 to 30 Hz with response down 3 dB maximum at 30 Hz. The controller is packaged as a complete, self-contained unit with integral power supplies and operates from 115 volts, 400 Hz, nominal supply power. The controller accomplishes the necessary amplification of command and feedback signals to provide accurate position response. The static threshold is 0.2 percent of full scale. Stability compensation networks produce damping of the servoloop response. The damping is sufficient to prevent overshoot or resonant responses exceeding 1.25 times the static response value.

4.1.2 Primary Actuators in the Rotating Frame

For purposes of this study, this actuation concept will be referred to as the Individual Blade Control Independent of a Swashplate (IBIS). The IBIS concept, illustrated in Figures 4-3 and 4-4, is a two-fail-operate system that employs two pitch horns and four actuators per blade. Each of the four actuators for a given blade is powered and controlled by a different power and signal source. The No. 1 actuator on each blade is powered by the No. 1 power supply and controlled by the No. 1 computer. The No. 2 actuator on each blade is powered by the No. 2 power supply, etc.

The power supplies are driven by stationary gears attached to standpipes. One standpipe is located inside the mast and extends above the rotor hub; the other is located outside the mast and extends to a point just below the hub. When the rotor is turning, the power supplies are activated through gear trains (Figure 4-5) as they rotate about stationary gears. There are two power supplies above the hub and two below.

Control commands and system condition data are transmitted through the rotating-nonrotating interface via fiber optics with redundant optic sliprings, one situated above and another below the rotor hub.

IBIS uses a single, unbalanced type actuator that is more reliable and economical than dual or triple actuators found on most medium to large production helicopters. The unbalanced feature reduces system power and weight by letting the smaller piston area share loads with the aiding oscillatory forces to reduce flow requirements. IBIS actuators use a dual seal design and are designed to be jam tolerant; but, should a jam occur, the force of three remaining actuators is available to free the jam. Installation and replacement of IBIS actuators is accomplished in

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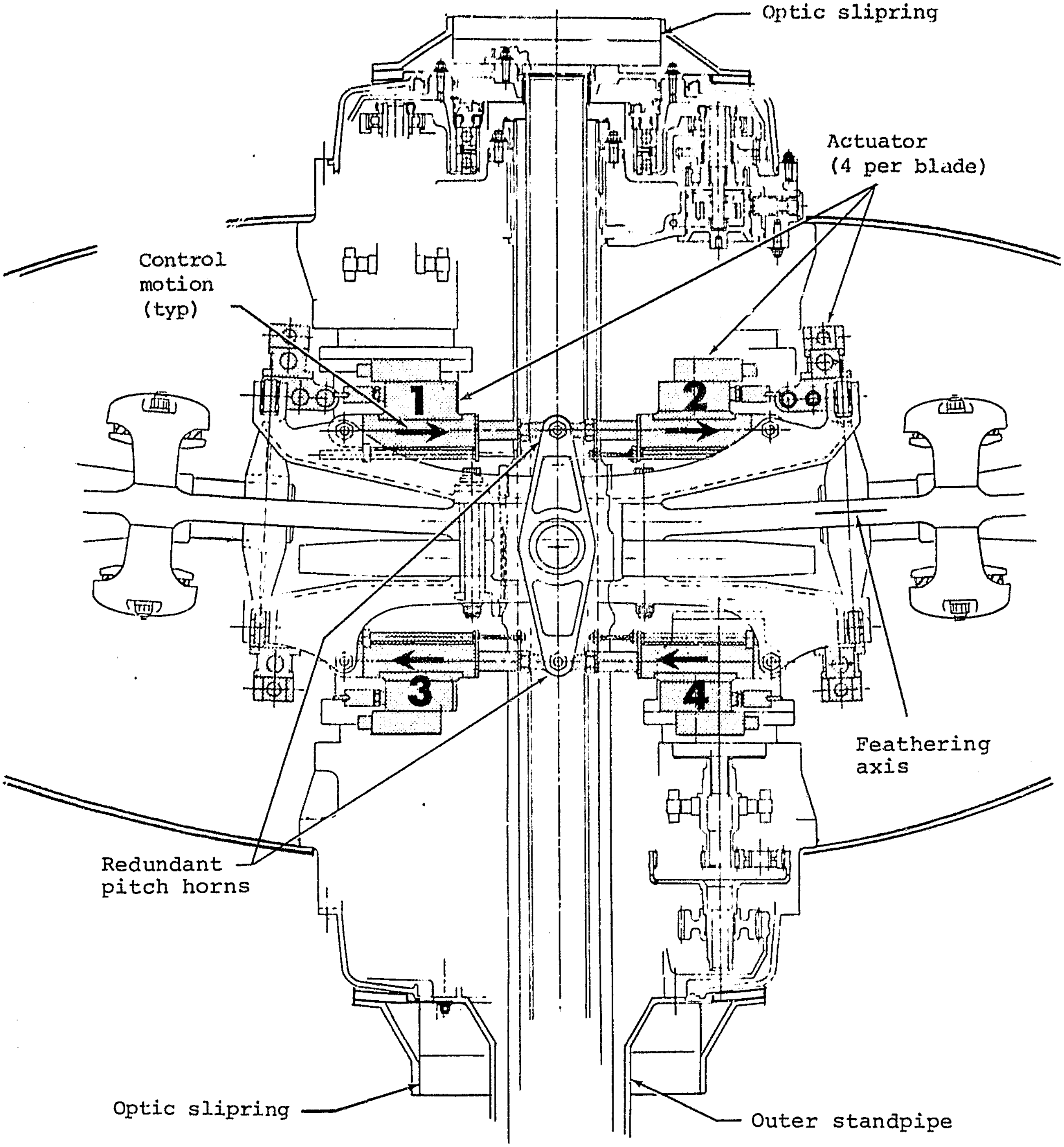

Figure 4-3. IBIS concept (side view)

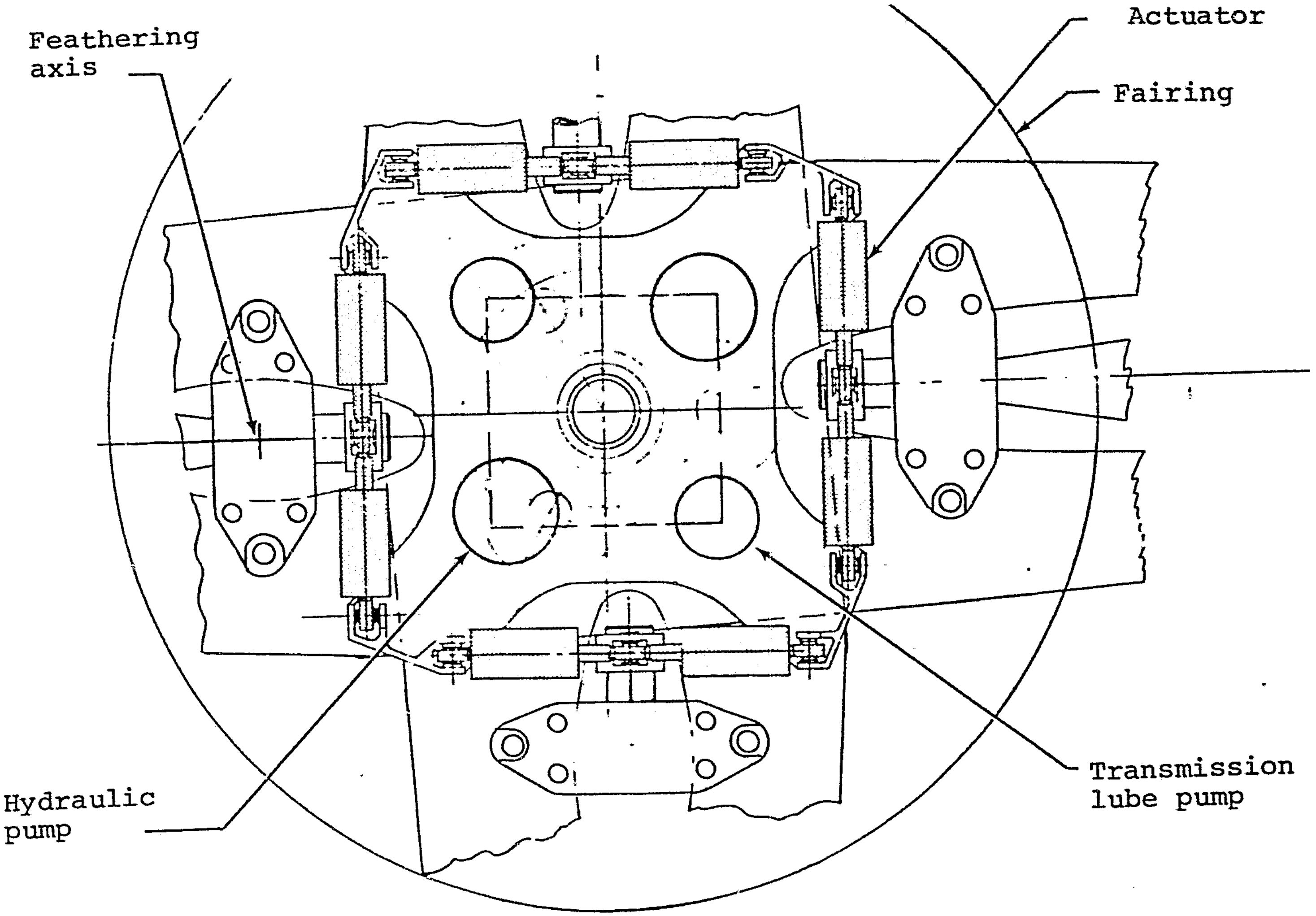

Figure 4-4. IBIS concept (top view).

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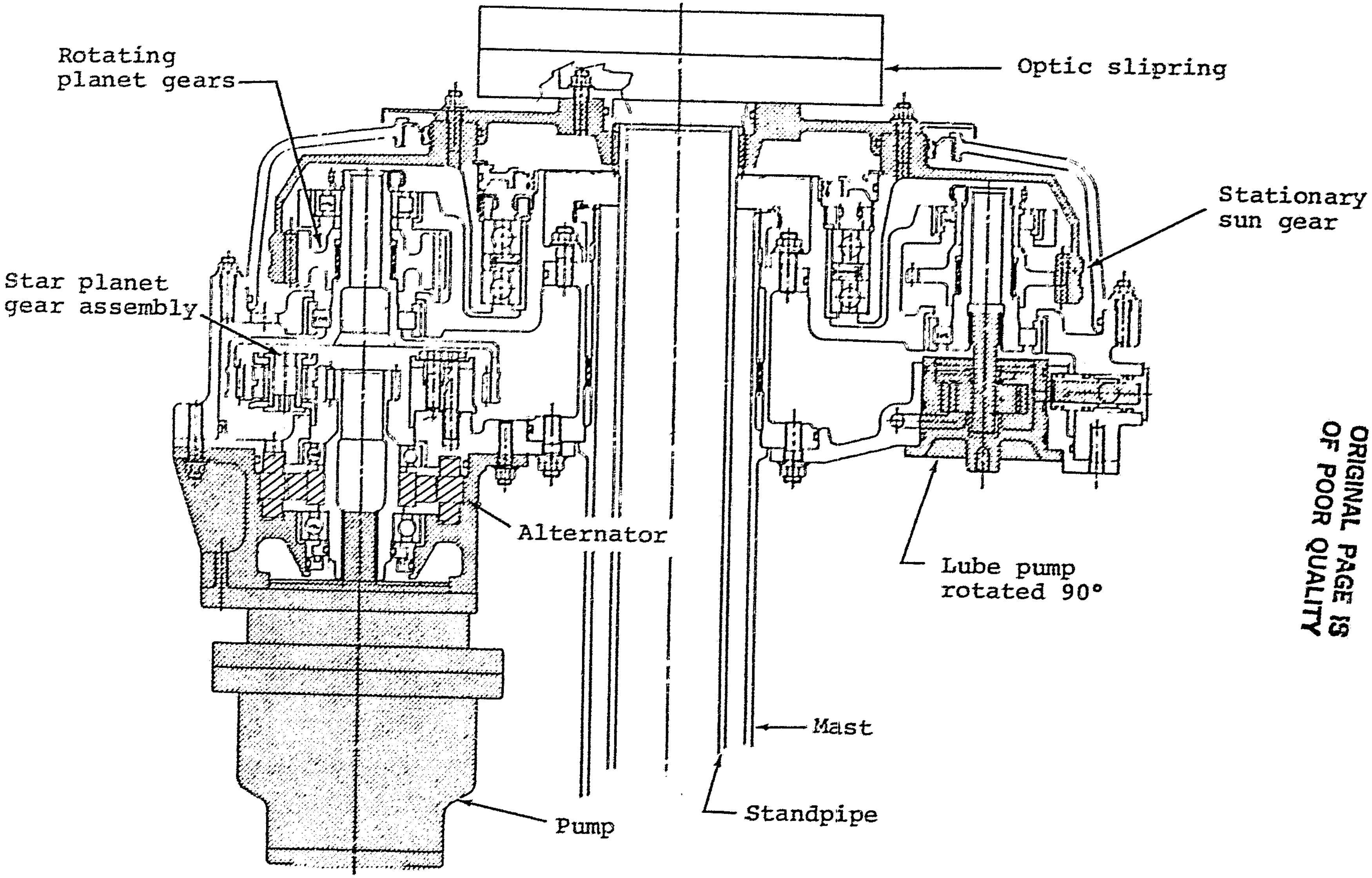


Figure 4-5. IBIS gear trains.

minutes with the use of hydraulic quick-disconnects that port fluid through a manifold that is an integral part of the actuator support.

4.1.2.1 Design Consideration. The IBIS control system was sized for the Model 412 in order to substantiate power requirements, component size and weight, heat generation, and required system cooling. At maximum gross weight and during maneuvers, the maximum measured Model 412 control loads are equivalent to IBIS pitch horn loads of 2540 pounds. Since two IBIS actuators must share this pitch horn load after two failures, they must be designed for a peak load of 1270 pounds each.

The IBIS pitch horn radius is 4.0 inches and must travel 2.75 inches to provide a total blade pitch of 40° (16° collective, 24° cyclic). With the Model 412 main rotor mast tilted 5° forward, the maximum forward cruise cyclic pitch required is ±9.4° or ±0.63 inch of actuator stroke. This actuator stroke occurs 5.23 cycles per second because the rotor speed is 314 rpm. The maximum forward cruise condition is the most severe for generating heat; therefore, this condition is used for establishing the heat transfer requirements.

4.1.2.2 Hydraulic Power Requirements. When all IBIS power supplies are operating normally, the required hydraulic pressure per pump at maximum cruise speed is 1200 psi. After one pump fails, this requirement increases to 2600 psi for the remaining three pumps.

When the second pump fails, the remaining two pumps must provide 4000 psi for maximum load conditions. Hence, the design is predicated on this emergency condition. But consider that in a conventional variable-volume/constant-pressure system, the power is a function of pressure multiplied by displacement. It is apparent that when all systems are functioning, the normal state, 2000 psi would be sufficient and save one-half of the power. Table 4-1 shows the hydraulic power savings due to the addition of the variable-pressure feature. It should be noted that savings can be made for flight conditions other than maximum cruise, as is shown by the 33 percent reduction in hover.

TABLE 4-1. IBIS HYDRAULIC POWER REQUIREMENTS

	Horsepower Requirements					
	4 Sys Operating		3 Sys Operating		2 Sys Operating	
	M.C.[1]	Hover	M.C.	Hover	M.C.	Hover
4000 psi constant pressure	36.0	18.0	27.0	13.5	18.0	9.0
Variable pressure	18.0	12.0	18.0	9.0	14.5	6.0

[1] Maximum cruise

Discussions with pump manufacturers indicated that little, if any, risk is involved in achieving a variable pressure system for the IBIS, with simple hydraulic logic (no electrohydraulic servovalve is required).

4.1.2.3 Electronics/Optics

Overall Signal Flow. Figure 4-6 illustrates the overall system for electronic control and redundancy management. Each group of four actuators operates one of the four main rotor blades by commands from individual digital signal processors to the respective electrohydraulic valves (EHVs). The EHV spool valve position and actuator position are fed back to each processor for control of actuator position, failure management, and control of force sharing of the actuators. LVDTs (linear variable differential transformers) are used to sense positions. Other LVDTs sense pilot's input command variables and provide signals for use by the processors. Separate sensor signals are fed into each channel from other sources, such as SAS and AFCS functions. The signals in the aircraft's nonrotating systems are all combined into each of four optical data links that pass signals to and from the rotating system via optical sliprings. Four independent electrical supplies operate the nonrotating system devices, such as the LVDTs, optical transmitter, receivers, etc. The rotating system also contains its own set of four electrical systems. Rotor azimuth pickups sense information needed to generate cyclic blade pitch functions.

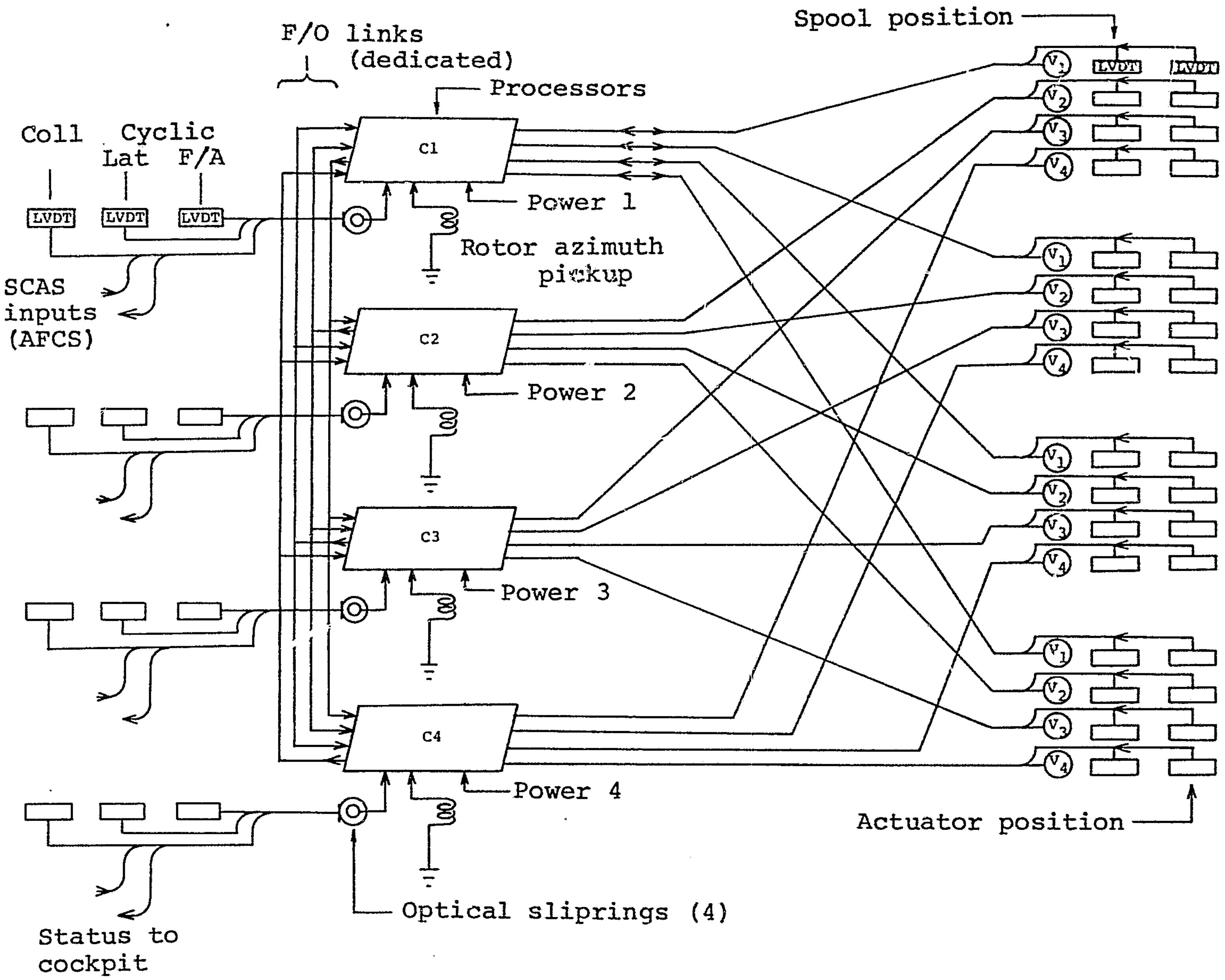


Figure 4-6. IBIS actuation signal paths.

Fault Management. Figure 4-6 shows a set of dedicated fiber-optic links that "broadcast" data from each processor to all the others. Since these links are the only cross-channel connections between the redundant system channels, optical links are used to eliminate propagation of electrical interference between channels.

Each processor sends status signals and signal values to the others for use in comparing signals for fault management. Information from each is compared, and status signals are generated for use in shutting down bad channels (or signal sources, in the case of non-flight-critical signals).

Overall Function. The primary control functions are mechanized by an architecture of four separate and independent signal source, processor, power source and actuation paths. The basic functions are generated by taking the input signals and generating the necessary sine and cosine cyclic and multicyclic control functions for each rotor blade. The individual rotor azimuth pickups provide a time reference for each processor to generate the appropriate function for its particular blade. In the case of multicyclic control, additional sensors such as accelerometers may be used if vibration reduction is a part of the overall system's needs.

The digital processors are selected to be able to handle the total needs of the control system. The speed, memory size, etc. are chosen to handle the basic control functions, SAS, AFCS, NAV couplers, etc. for an optimally integrated system.

Force Sharing. To keep the actuators in an equal force-sharing mode, the optical links are used to send data from each processor to the others. The EVH spool position signals are compared, and correction signals generated to equalize the spool positions. This process uses limited authority of the correction signals compared to command signals. This allows maintenance of control (slightly degraded) even though any number of spool position LVDTs fail. This can be done because force imbalance is a performance or fatigue life factor as opposed to critical flight safety. The spool LVDTs serve also to provide failure indication information to the fault management algorithms.

Processors. Figure 4-7 is a block diagram of the processors (C1 through C4) shown in the overall signal path diagram (Fig. 4-6). The basic architecture is one where special function processors are used to handle input/output (I/O) and mathematical functions. The optical signals are multiplexed through a common fiber-optic receiver and sent to the I/O processor. Likewise, other optical

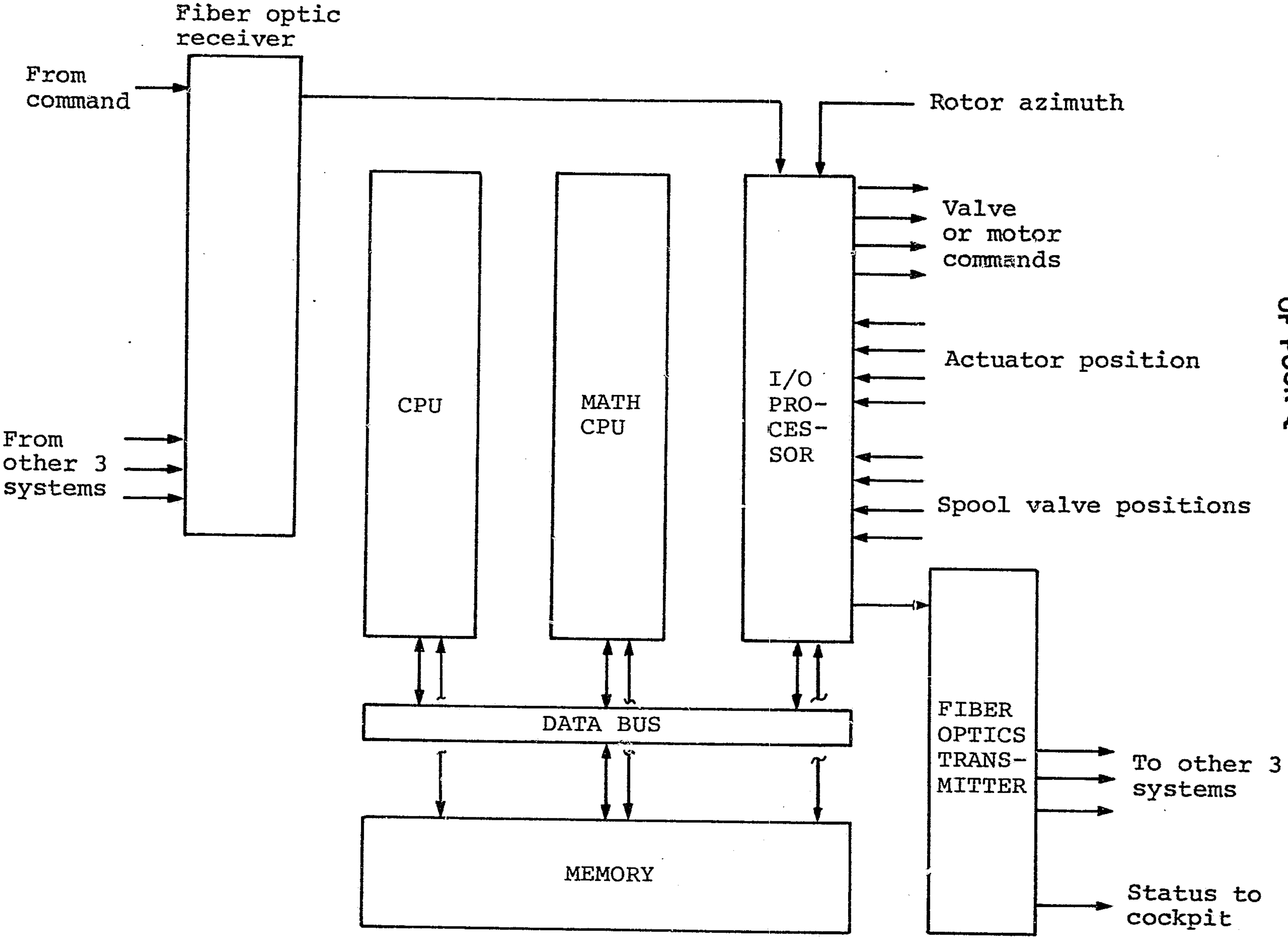


Figure 4-7. IBIS processors (1 of 4)

and electrical signals are multiplexed into and out of the system. The math processor is used to execute complex math functions, such as multiply, divide, trigonometric, and logarithmic functions, as needed by the flight controls and other system functions. The processing system consists of the CPU and two co-processors.

4.2 RELATED COCKPIT TECHNOLOGY

Civil mission analyses have indicated several areas for improved design of both controls and displays. They fall into the following categories:

a. Control area improvements:

  (1) Hover, auto and fly-through [hover coupler (Doppler + AHRS)]

  (2) Nav, point-to-point

  (3) Low-airspeed control

  (4) Decoupled controls

  (5) Performance, vector control

b. Display area improvements

  (1) Improved external visibility

  (2) Improved map data

  (3) Improved systems monitoring with internal and external vision

  (4) Improved display monitoring with internal and external vision

  (5) Improved data on aircraft performance, predicted performance, and fuel conservation

To coordinate the RCT section of this report with the ACT section is not straightforward; they are almost independent. Improvements in controls could exist with conventional displays and cockpit configurations. Improved cockpits with advanced integrated displays could, and do, exist with conventional controls and controllers.

It is, however, fitting to consider that as the ACT improves, the

RCT will also improve. Table 4-2 outlines the improvements of the ACT and as these advance, improvements in RCT are also indicated.

Three cockpit displays are considered. These may be seen in Figure 4-8. Panel 1 shows the conventional BHTI model instrument panel. Panel 2 is a first improvement. Cathode ray tube (CRT) displays have replaced the primary flight displays. Control display units (CDUs) have been added for the NAV/COM functions. Caution/warning displays have been incorporated into the CDUs, as have certain of the engine-monitoring tasks. A voiced display has been added to provide caution/warning redundant information.

Panel 3, the final RCT panel for this report, has incorporated a full integrated digitized system with multifunction displays replacing existing displays. The only remaining dedicated displays are tachometer and torque. Standby instruments are provided in the center of the panel to be time-shared by the pilot and copilot. Because of the design, the size of the panel can be reduced by approximately 16 percent in panel width. Added features to Panel 3 are voiced audio displays. These could include not only caution/warning information and checklists but audio readouts of any flight or system parameter the pilot might choose. For example, when precision hover is critical, the voiced display would be programmed to read lateral and fore-aft deviations from a given spot and precise altitude. It would also read tachometer or torque information and airspeed or groundspeed. All of these would be at the pilot's selection and at a rate he chose.

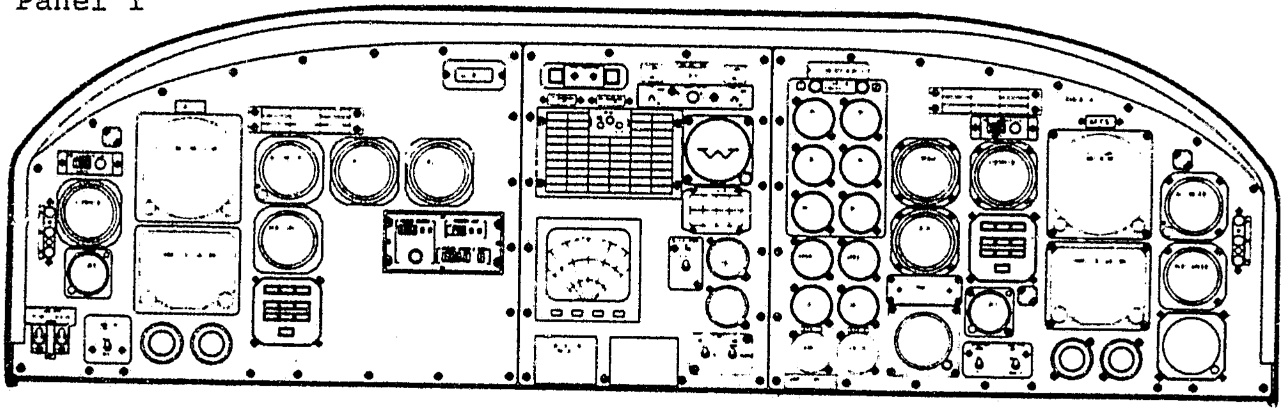
Panel 3 would also include a helmet, or head-mounted display (HMD), on which flight, navigation, or system performance data would be a pilot option. This type of display would be useful in critical areas of selected missions such as IFR approach, night navigation and landing approach, and precision hover for logging or rescue.

Currently, a miniaturized head-mounted display is being developed at BHTI (Ref. 10) that weighs less than 4 ounces and is capable of providing all moving symbology and numeric data needed for such missions. A sketch of this display system is shown on Figure 4-9. This display is compatible with the night vision goggles. The proposed control would be a side-arm-mounted force control on the right side controlling three axes (pitch, roll, and yaw). The left-hand control would be a side-arm, single-axis, position-movement collective. On these controls would be hands-on controls to activate the multifunction displays (MFDs). Figure 4-10 shows conventional military cyclic and collective grips with hands-on switches to control MFDs.

TABLE 4-2. ACT/RCT CONCEPTUAL DESIGN OPTIONS

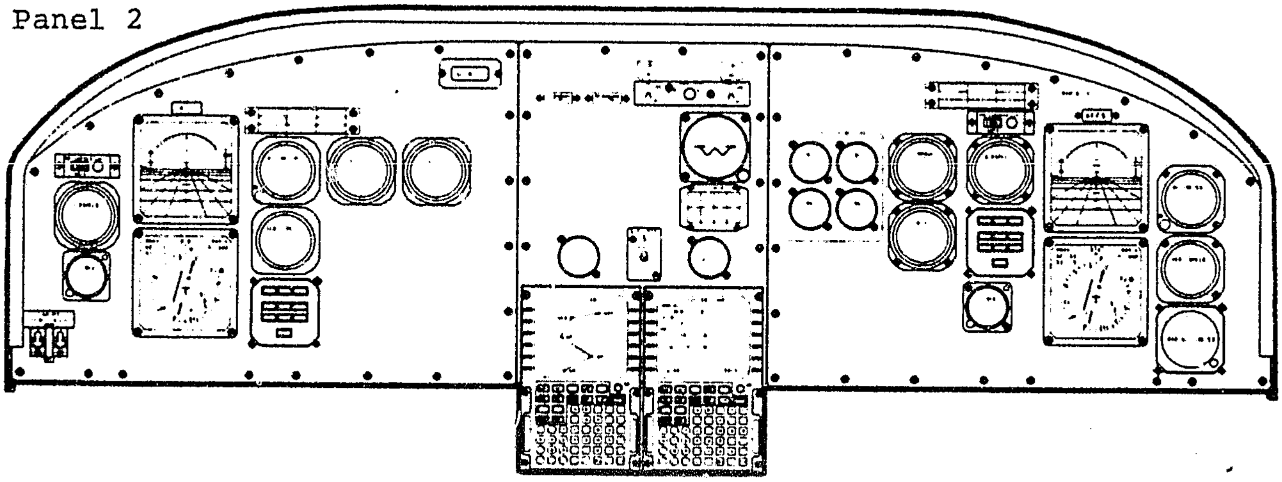
Active Control Technology (ACT)		Related Cockpit Technology (RCT)	
Actuation	Control Laws	Controllers	Display
		Cockpit 1	
Series actuators	Conventional SAS	Conventional	Panel 1
		Cockpit 2	
Primary power actuators	Discrete SAS combined with optional control algorithm	Automatic trim Hover coupler Force controller 3-axis controller	Panel 2 plus · Head up display (HUD) · Voiced caution/ warning · Night vision · Aircraft performance
		Cockpit 3	
Individual blade control, rotating system	Discrete SAS combined with optional control algorithm	Automatic trim Hover coupler Vector control Force controller 3-axis controller Interactive voice controller	Panel 3 plus · HMD (micro-HUD) · Voiced caution/ warning · Voiced director · Voiced parameter monitor · Night vision · Aircraft performance · Fuel conservation · System performance predictor

Panel 1



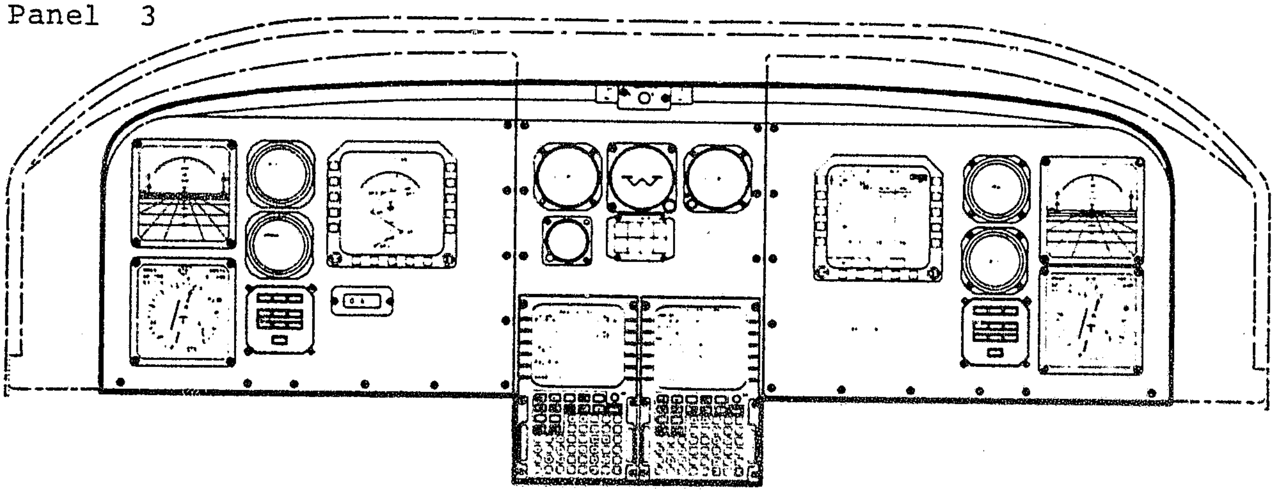
a. Conventional panel.

Panel 2



b. Interim integration of NAV-COM data with CRTs for VSI and HSI.

Panel 3



c. Full information display integration.

Figure 4-8. Instrument panel evolution.

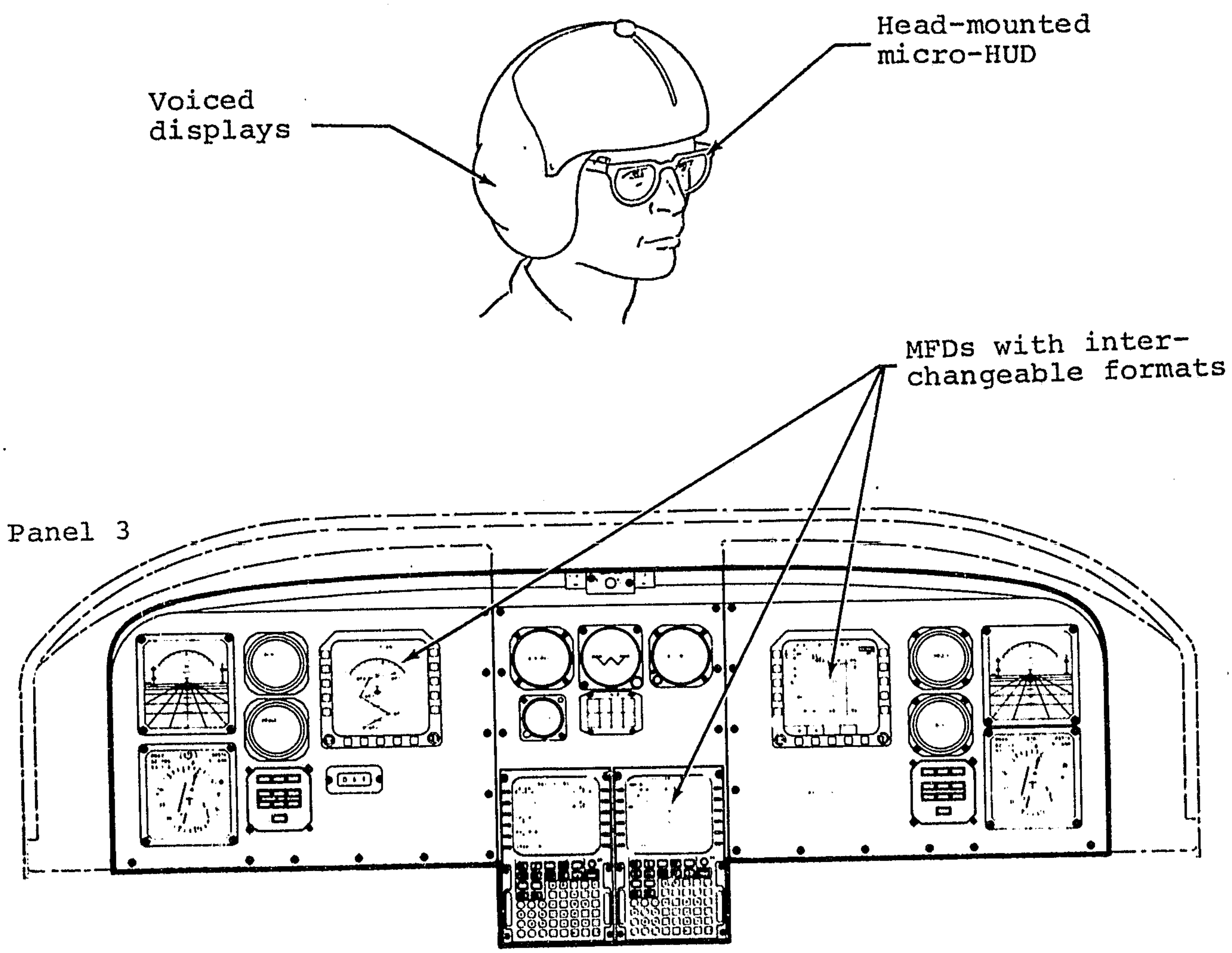
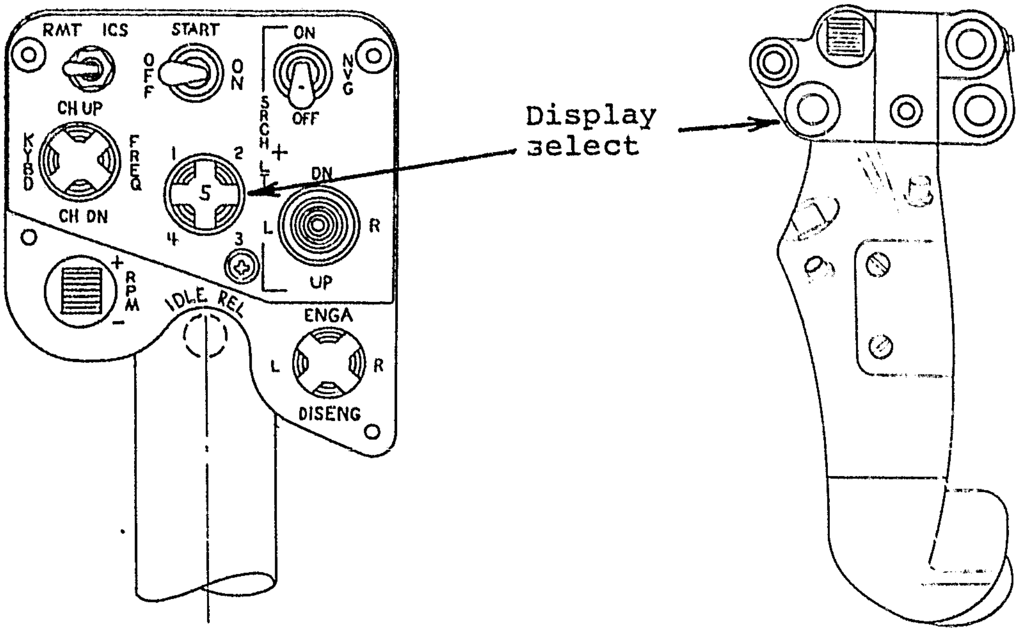


Figure 4-9. Proposed RCT advanced helicopter display system.



Display select

COLLECTIVE

CYCLIC

Figure 4-10. Conventional military cyclic (right) and collective (left) control heads.

5. BENEFITS ASSESSMENT

The benefits of active control technology and related cockpit technology to rotorcraft are quantified in this section. The benefits of HHC, or multicyclic control, are assessed without regard to where the high-frequency actuators are located. If the control commands are input below the swashplate, both collective and cyclic frequency commands are made at 4/rev, in the case of the four-bladed Model 412 rotor. In systems with actuators in the rotating frame, the cyclic excitation is made at 3/rev and 5/rev, although the 5/rev component may not be essential. In full-scale helicopters, excitation below the swashplate may prove less than ideal.

Other benefits of active control in the rotating frame are also assessed. These benefits include reliability, maintainability, performance in the form of drag reduction, weight, and, finally, the unique potential for vibration deicing of the rotor blades. Additionally, the influence of the related cockpit technology on pilot workload is assessed.

5.1 ACTIVE CONTROL TECHNOLOGY

5.1.1 Higher Harmonic Control

The analytical investigation of the effects of higher harmonic controls (HHC) on helicopter fuselage vibrations and performance was conducted using a special version of the Rotorcraft Flight Simulation Program C81. The BHTI production version of C81, AGAP8003, has the ability to calculate the effects of specified HHC inputs on the shears and moments transferred from the rotor to the mast, and on the rotor's aerodynamic performance. A complete description of the aeroelastic rotor analysis based on the modal approach is contained in References 11 and 12.

The special version of C81 was created to search, on an iterative basis, those values of HHC inputs that would eliminate specific components of the hub shears and moments. It is assumed in the mathematical model that the major oscillatory hub shears and moments occur at b/rev (where b is the number of blades) and that the conventional main rotor control inputs can be feathered at b/rev. This provides six independent control inputs: magnitude and phase angle for b/rev feathering of collective, longitudinal cyclic, and lateral cyclic inputs. By selecting the magnitude and phase angles of three load components at the hub, it becomes possible to write

$$\underset{6\times1}{\{F\}} = \underset{6\times6}{[T]}\ \underset{6\times1}{\{\delta\}} \qquad (1)$$

where $\{F\}$ is the load vector, $\{\delta\}$ is the control input vector, and $[T]$ is the transfer matrix. The variation in $\{F\}$ due to a change in the control inputs can be written as

$$\underset{6\times1}{\{\Delta F\}} = \underset{6\times6}{[T]}\ \underset{6\times1}{\{\Delta\delta\}} \qquad (2)$$

From Equation 2, it follows that the t_{ij} element of $[T]$ can be interpreted to the change of the i^{th} load component produced by a change in the j^{th} control input. For any desired change in $\{F\}$ Equation 2 can be solved to obtain the required inputs as

$$\{\Delta\delta\} = [T]^{-1}\ \{\Delta F\} \qquad (3)$$

If $\{\Delta F\}$ is chosen as the negative of the oscillatory load components of the baseline case, then the control inputs, $\{\Delta\delta\}$, when applied to the baseline case, should eliminate the baseline oscillatory load components.

This procedure has been incorporated in the special-purpose version of C81. Starting from the baseline case in C81, the six components of the HHC are individually and sequentially incremented with the resulting change in all six load components being recorded internally to define fully the [T] matrix. Once the [T] matrix has been inverted, simple matrix premultiplication of the negative of the baseline load components gives the required control inputs, which are used automatically in the subsequent analysis. The flow chart for this process is shown in Figure 5-1.

The flight conditions for a Model 412 helicopter were selected to cover the flight envelope. The matrix of flight parameters was:

Gross weight	7500 lb, 11600 lb
Center-of-gravity station	130 in, 144 in
True airspeed	80, 110, 130 kn

Baseline cases, i.e., those without any higher harmonic control inputs, were obtained for all 12 combinations of the flight parameters stated above. The three shears, pitch moment, and roll moments occurring at multiples of the blade passage frequency were recorded for each case. These data are contained in Appendix B.

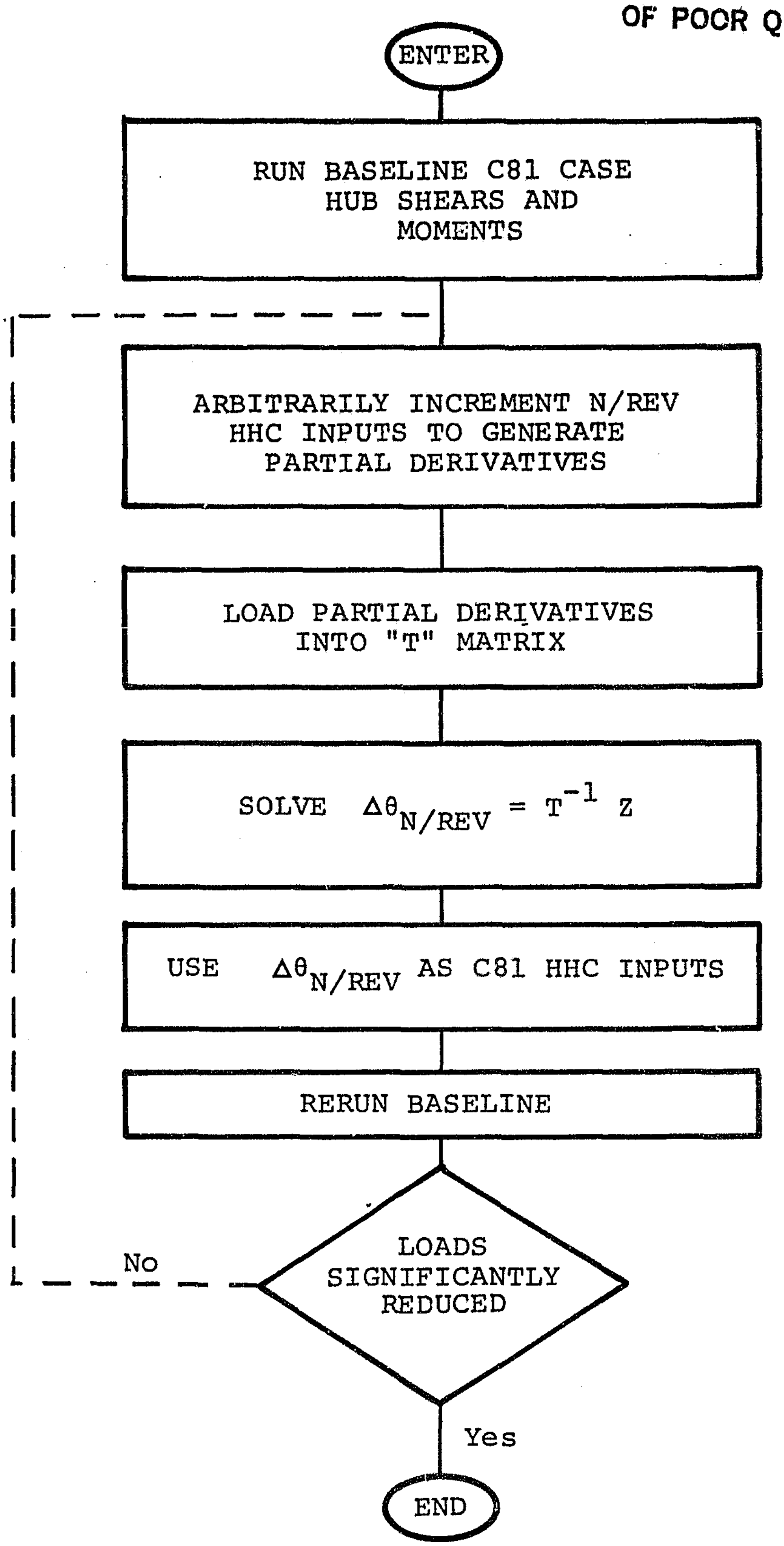


Figure 5-1. HHC flow chart.

The results in Table 5-1 show that for the best case (GW = 11,600, cg = 144, V = 80) the control law algorithm reduced the oscillatory 4/rev shear resultant from 82.4 pounds to 7.6 pounds, which is 9.3 percent of the baseline value. At the light-gross-weight, high-speed condition, the control law algorithm reduced the 4/rev oscillatory shear to 46 percent of the baseline value.

While obtaining the results in Table 5-1, two particularly interesting effects were noticed. The first was related to the repeated application of the control correction as given by Equation 3. The baseline oscillatory 4/rev shear at V = 125, cg = 144, GW = 11,600 was calculated to be 226.0 pounds. The first application of a higher harmonic input reduced the shear to 82.2 pounds. Reapplication of the control law produced a vertical shear of 93.3 pounds, which is greater than that obtained during the first application of the derived control inputs. It was found that by using a fractional part of the second derived control input, the resulting oscillatory shear loads could be reduced.

Some investigators have questioned the effectiveness of HHC at high advance ratios, i.e, $\mu > 0.2$. Since the previously mentioned best case corresponds to $\mu = 0.18$, it should be worthwhile to examine a case with a higher advance ratio. For $\mu = 0.29$, GW = 11,600, cg = 144, and V = 130, the first iteration resulted in a shear resultant of 20 percent of baseline, reducing the ±279 pound load to ±57 pounds. The input to achieve this reduction was the equivalent of ±0.12° of collective, ±1.00° of longitudinal cyclic, and ±0.92° of lateral cyclic 4/rev pitch change at the blade root. In the other high gross weight (11,600 pounds) case at 130 knots, i.e., cg = 130, the control law algorithm reduced the shear resultant to 13 percent of the baseline. The blade pitch change to achieve this reduction was ±0.17° collective, ±1.50° longitudiual cyclic, and ±1.35° lateral cyclic.

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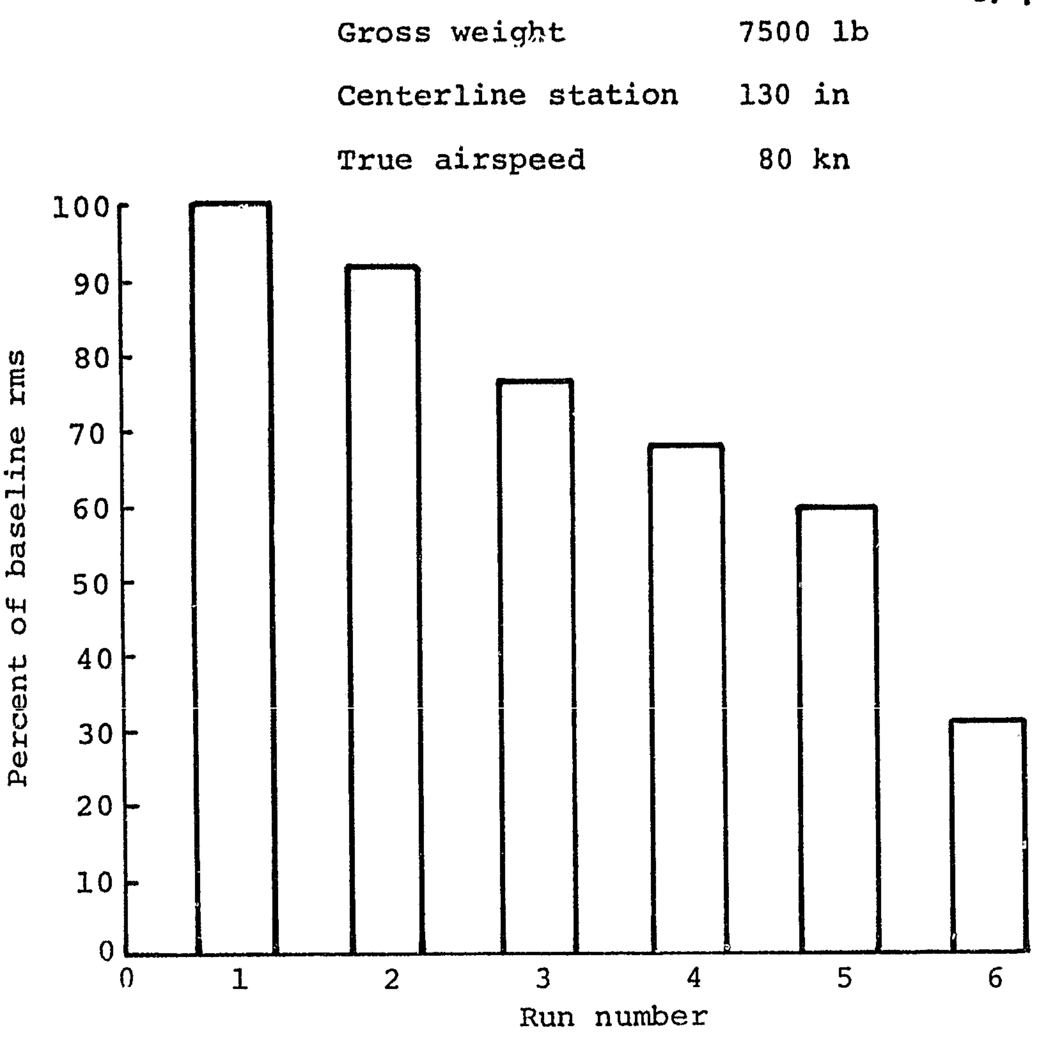
TABLE 5-1. RESULTS OF XYZ SHEAR MINIMIZATION BY HIGHER HARMONIC CONTROL

Gross Weight (lb)	CG (in)	Airspeed (kn)	Oscillatory Shear Resultant (± lb) Baseline (lb)	Oscillatory Shear Resultant (± lb) Improved (lb)	Improvement (% of Baseline)
11,600	130	80	120.0	43.8	36.2
	130	110	213.3	63.9	29.9
	130	130	370.0	48.9	13.2
11,600	144	80	82.4	7.6	9.3
	144	110	149.3	26.1	17.5
	144	130	278.8	62.0	22.1
7,500	130	80	63.8	19.6	30.6
	130	110	176.2	52.4	29.7
	130	130	296.0	136.0	46.0
7,500	144	80	59.6	26.7	44.0
	144	110	165.0	27.0	16.3
	144	130	261.0	121.0	46.0

The investigation revealed the fact that the algorithm effectivity can be influenced by the increment size used in numerically defining the [T] matrix. This effect is demonstrated by the case with GW = 7500, cg = 130 and V = 80. The baseline oscillatory shear is 63.84 pounds at 4/rev. Using a 0.15° collective increment and a 1.0° cyclic increment in calculating the control sensitivity matrix produced an oscillatory shear of 58.4 pounds. However, using a control increment of 0.025° for both the collective and cyclic pitch in defining the [T] matrix produced a shear of 19.6 pounds, or 31 percent of baseline. Results obtained from other control inputs are shown in Figure 5-2.

Closer inspection of this unusual effect revealed that it can often be produced by nonlinearity in the mathematical model. This effect requires close management to achieve a satisfactory resolution.

The results tabulated in Table 5-1 are plotted in a before and after fashion in Figure 5-3. Here, the light gross weight data have been omitted, in spite of the fact that only two data points fall outside of the band labeled "WITH HHC." Both of the data points resulted from runs completed before the sensitivity to increment size was discovered.



Run Number	Coll	F/A	Lat
1	— — —	Baseline	— — —
2	0.15	1.0	1.0
3	0.5	1.0	1.0
4	1.0	1.0	1.0
5	0.05	0.05	0.05
6	0.026	0.025	0.026

Figure 5-2. Influence of increment size on optimization.

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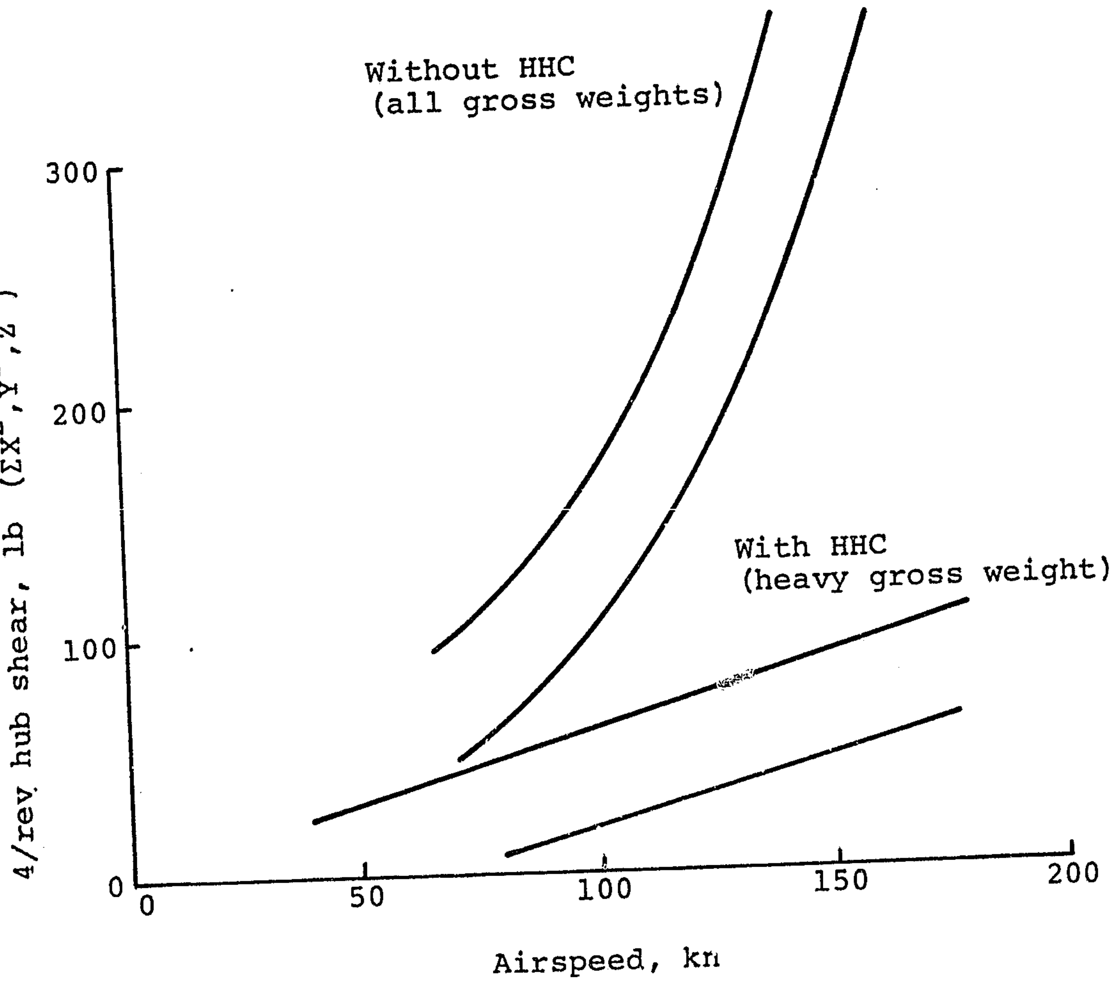

Figure 5-3. Hub shear with and without HHC.

All results presented thus far have been based on eliminating the X, Y, and Z shear components at the top of the mast. The effect of minimizing other load components was investigated for the case of GW = 7500, cg = 144, and V = 125. This case was run to minimize the 4/rev resultant of the Z shear, pitch moment, and roll moment.

The results showed a vector sum of 12.2 percent of baseline on the first iteration. Here again, it was verified that a small increment (0.025° collective and cyclic pitch) used in defining the [T] matrix produces good results. Accompanying this reduction was an increase in total oscillatory pitch link load from ±156 to ±178, or 7.7 percent. The power, as determined from the mast torque, increased from 1017 to 1023 horsepower.

As an indication of the accuracy of the C81 math model, it should be noted that flight test data for the baseline case indicate a total pitch link load of ±168 pounds, 6.4 percent higher than predicted by C81.

5.1.2 Reliability and Maintainability

Reliability and maintainability prediction analyses of the baseline BHTI Model 412 helicopter and the selected ACT/RCT configuration are reported here. For purposes of this study, the BHTI Model 412 is considered to be identical to the UH-1N, the military version, with regard to the controls and cockpit.

Prediction analysis data for the UH-1N were developed recently under NASA Contract NAS2-10277 (Ref. 13). While these data are extremely detailed relative to inherent failure rates and maintainability requirements, no safety-of-flight reliability analysis was performed. Therefore, it was necessary to perform this analysis during the current contracted effort. The results are reported in subsequent paragraphs.

In Reference 13, Navy maintenance and material management (3M) system was selected as a data source because BHTI maintains a complete file of these data on the UH-1N helicopter. The data for calendar years 1977 and 1978 were used. These included 70,952 flight-hours on 190 UH-1N helicopters. The system definitions were obtained using BHTI's flight control system drawings for the flight control system configuration of the UH-1N.

The work unit code (WUC) manuals, NAVAIR 01-110HC-8 for H-1 helicopters were used to identify parts in the 3M data. The 3M data were used to obtain the rates in the reliability analysis and the maintenance man-hours per task for the unscheduled maintenance. The scheduled maintenance rates were obtained from the NAVAIR 01-110HCE-6 series UH-1N maintenance cards.

As a measure of the safety-of-flight reliability for the medium turbine class helicopter, a search of the National Transportation Safety Board records for the period from 1970 through 1978 indicated two accidents attributed to the flight controls in 1.2 million flight-hours or 1.67 per million flight-hours.

5.1.2.1 Baseline Helicopter Reliability Analysis. The reliability analysis from Reference 13 included the calculation of the following reliability parameters at the line replaceable unit (LRU), subsystem, and system levels:

a. Failure rate, λ_F, based on inherent failures only. Externally caused failures are not included.

b. Unscheduled replacement rate, λ_R, based on inherent failures that resulted in part replacement.

c. Unscheduled adjustment rate, λ_A, based on inherent failures that did not result in part replacement.

d. Preflight aborts, λ_p, based on inherent failures resulting in mission abort. This is also referred to as the dispatch abort rate.

e. Inflight abort, λ_I, based on all inflight aborts.

These analyses were made using the 3M data that were received from the Navy on magnetic tape, and BHTI reliability analysis computer programs. All of the parameters above were extracted directly from the 3M analyses with the exception of the unscheduled adjustment rate. This was calculated using the following equation:

$$\lambda_A = \lambda_F - \lambda_R$$

Tables 5-2 and 5-3 summarize the reliability parameters.

5.1.2.2 Baseline Helicopter Maintainability Analysis. The maintainability analysis consisted of identification of the following values:

a. Man-hours for scheduled replacement

b. Man-hours for unscheduled replacement

c. Man-hours for adjustment

d. Man-hours for inspection

TABLE 5-2. UH-1N BASELINE RELIABILITY SUMMARY: FAILURE RATES

Control Subsystems	Failures per Million Flight hours			
	Adjustments	Replacements	Preflight Aborts	Inflight Aborts
Cyclic controls	4902	2661	455	382
Stick instl., collective/ throttle	2361	170	88	56
Collective controls	1791	370	92	201
Throttle controls	4455	689	239	110
Main rotor controls	13,626	2573	1055	357
Antitorque controls	6774	1017	181	279
Elevator controls	644	32	32	6
TOTAL	34,553	7512	2142	1391

TABLE 5-3. UH-1N BASELINE RELIABILITY SUMMARY: MEAN FLIGHT-HOUR VALUES

Control Subsystem	Mean Time Between Failures	Mean Time Between Dispatch Aborts	Mean Time Between Inflight Aborts
Cyclic controls	132	2,198	2,618
Stick instl., collective/ throttle	395	11,364	17,857
Collective controls	463	10,870	4,975
Throttle controls	194	4,184	9,091
Main rotor controls	62	948	2,801
Antitorque	128	5,525	3,584
Elevator controls	1,479	31,250	16,667
TOTAL	23.8	467	719

e. Mean-time-to-repair (MTTR) and maintenance-man-hour-per-flight-hour (MMH/FH) values for the actuation system.

After the preliminary steps were completed, a computer program was used to calculate the above values. The man-hours for scheduled and unscheduled replacement were established at the component level using the computer. These component values were combined, and a mean replacement time for each subsystem was calculated.

A similar computer program was used to calculate adjustment man-hours. Because the WUC system allows adjustment time to be reported under several codes, such as "calibration" and "repair," the computer program was set up to combine several codes. These values were then combined and a mean value determined for each subsystem.

Man-hours for inspection were determined from the inspection cards for each aircraft. Specifically, the card sets were

UH-1N - NAVAIR 01-110ACE-6-3 and -4
dated 1 September 1975

Where there were several components to be inspected in a given area, the actuation system inspection time was based on the percentage of the number of components in the area.

The results of these analyses are summarized in Table 5-4 and were also used as inputs to the cost analysis.

The MTTR values for the UH-1N were obtained from data tab runs that included all maintenance, that is, unscheduled repairs as well as replacements were included. The MTTR, N (number of men per task), and MMH/FH were determined to be

MTTR	2.91
N	2.20
MMH/FH	0.17

5.1.2.3 Baseline Helicopter Reliability and Maintainability Summary. The reliability and maintainability values obtained for the baseline helicopter are summarized below:

MTBF	-	Mean time between failures	23.8 hr
MTBR	-	Mean time between removals	133.1 hr
MTBPFA	-	Mean time between preflight aborts	467 hr
MTBIFA	-	Mean time between inflight aborts	719 hr
MTTR	-	Mean time to repair	2.9 hr
MMH/FH	-	Maintenance man-hours per flight-hour	0.17 hr

TABLE 5-4. UH-1N MAINTAINABILITY ANALYSIS SUMMARY

Work Unit Code	System/Subsystem	Scheduled Replacement (MH/Task)	Unscheduled Replacement (MH/Task)	Adjustment (MH/Task)	Inspection (MH/Task)
11000	Flight control system	-	-	-	Turnaround 0.1 Daily 0.3 Phase 1.3 Special 0.1
	Fixed controls Stick -	-	16.02	2.99	-
	Cyclic -	-	11.15	4.26	-
	Collective -	-	14.10	3.57	-
	Throttle -	-	2.86	3.60	-
	Rotating controls	3.42	11.70	2.57	-
	Antitorque	-	4.82	3.09	-
	Elevator controls	-	10.14	3.38	-

5.1.2.4 IBIS Reliability Analysis. The reliability and maintainability predictions are based on the block diagram in Figure 5-4. It is readily apparent from this figure that the optical sliprings, gearboxes, and other components arranged in series contribute significantly to the failure rates for the two systems, each with pairs of LVDTs for the lateral and longitudinal cyclic and the collective, and single optical sliprings and gearboxes.

Based on BHTI's long history of helicopter transmission development and production, the flight safety failure rate of these gearboxes is estimated to be 5 per million flight-hours. In the case of the optical sliprings, a mature technology device should have a flight safety failure rate of 100 per million hours. The failure rates for all components are listed in Table 5-5. Loss-of-function failures shut down one system. Unscheduled maintenance failures do not cause loss of function, but do create a requirement for maintenance.

Loss-of-function failures in both LVDTs of any one pair (lateral, collective, or longitudinal) in one of the systems will cause a shutdown of that system. The failure rate for shutdown of that system due to failure of a pair of LVDTs is

$$\lambda_{LVDT} = (\lambda_{lat})^2 + (\lambda_{coll})^2 + (\lambda_{long})^2$$

$$= 0.000036 \text{ failures per million hours}$$

The remaining system will provide the control function to the actuators.

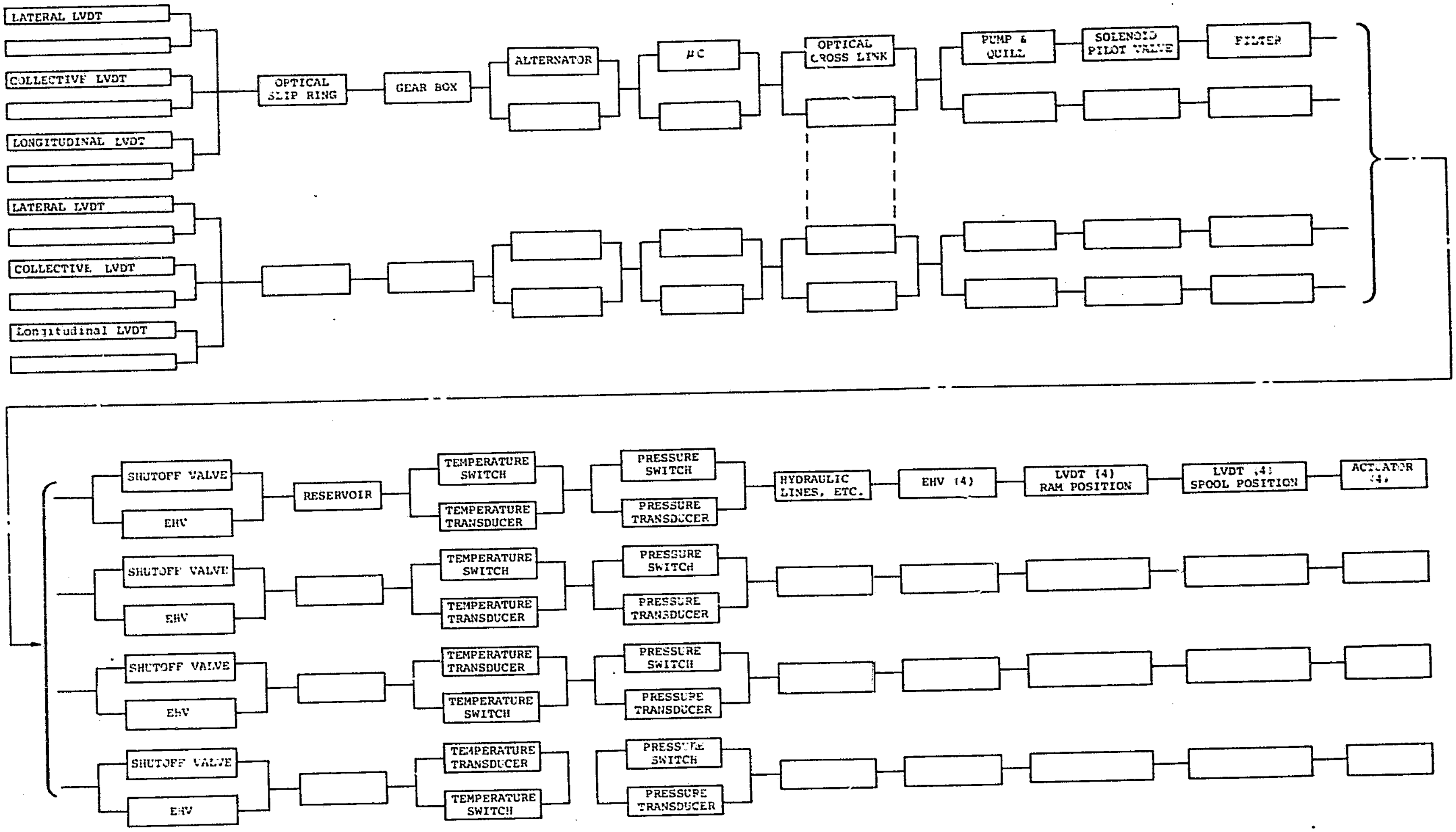

Figure 5-4. Reliability block diagram.

TABLE 5-5. IBIS RELIABILITY SUMMARY

	Failures Per Million Hours			
	Loss-of-Function Failures	Unscheduled Maintenance Failures		
Component		λ_F	Quantity	Total λ_F
LVDT (sticks)	3.45	3.45	12	41
Slipring	100	200	2	400
Gearbox	5	1000	2	2000
Alternator & elect. supply	13.8	250	4	1000
μC	200	295	4	1180
Optical crosslink	20	25	4	100
Quill & pump	33	609	4	2436
Solenoid pilot valve	11.38	55	4	220
Filter	-	-	-	-
Shutoff valve	11.8	55	4	220
EHV	12.3	-	-	-
Reservoir	14	28	4	112
Temp switch	24	125	4	500
Temp transfer	50.5	250	4	1000
Press switch	24	125	4	500
Press transducer	50.5	250	4	1000
Hyd lines, etc.	123	239	4	956
EHV (4)	49.2	12.3	16	196
LVDT (4) RAM	13.8	3.45	16	55
LVDT (4) spool	13.8	3.45	16	55
Actuator (4)	88	277	16	3960
TOTAL UNSCHEDULED MAINTENANCE FAILURES				17,931

The total failure rate for the shutdown of one system is

$$\begin{aligned}\lambda_{\text{shutdown one system}} = {} & \lambda_{\text{LVDT}} + \lambda_{\text{slipring}} + \lambda_{\text{gearbox}} + \\ & (\lambda_{\text{alternator}})^2 + (\lambda_{\mu c})^2 + \\ & (\lambda_{\text{cross link}})^2 + [\lambda_{\text{pump and quill}} + \\ & \lambda_{\text{solenoid}} + \lambda_{\text{filter}} + (\lambda_{\text{shutoff valve}})(\lambda_{\text{EHV}}) + \lambda_{\text{reservoir}} + \\ & (\lambda_{\text{temp sw}})(\lambda_{\text{temp trans}}) + \\ & (\lambda_{\text{press sw}})(\lambda_{\text{press trans}}) + \\ & \lambda_{\text{hyd}} + \lambda_{\text{EHV}} + \lambda_{\text{LVDT RAM}} + \lambda_{\text{LVDT spool}} + \lambda_{\text{actuator}}]^2\end{aligned}$$

Failure rates for this equation are the loss-of-function failures in Table 5-5.

$$\begin{aligned}\lambda_{\text{shutdown one system}} = {} & 0.000036 + 0.000100 + 0.000005 + \\ & (0.000150)^2 + (0.000200)^2 + \\ & (0.000020)^2 + [0.000033 + 0.000011 \\ & + 0.0 + (0.000012)(0.000012) + \\ & 0.000014 + (0.000024)(0.000051) + \\ & (0.000024)(0.000051) + 0.000123 + \\ & 0.000049 + 0.000014 + 0.000014 + \\ & 0.000088]^2 \\ = {} & 0.00014 \text{ failures per hour}\end{aligned}$$

The mean time between failure (MTBF) for the shutdown of one system is 7,140 hours.

Loss of function of both systems would create a flight safety situation. The flight safety failure rate is

$$\lambda_{\text{flight safety}} = (\lambda_{\text{shutdown one system}})^2$$
$$= (0.00014)^2$$
$$= 1.96 \times 10^{-8} \text{ failures per hour}$$

5.1.2.5 IBIS Maintainability Analysis. Based on the failure ratio λ_F in Table 5-5, the maintenance MTBF for the IBIS is 55.7 hours. Some uncertainties exist, however. The effect of centrifugal force, however small, on most of these components has not been documented. The failure rate for the reservoir may be unconservative unless a bellows type (no sliding seal) unit is developed for this application. Additionally, the failure rate of the actuator is based on AH-1J 3M data. At first glance, this failure rate might appear optimistic, considering the 1/rev cyclic motion required; however, the actuators on the baseline helicopter are subjected to 2/rev feedback loads that cause small oscillatory motion (or "dither"), resulting in wear on both the seal and the piston rod. Also, seals on the baseline helicopter are designed for low friction or breakout force. No such restriction is required on IBIS actuators and, more specifically the IBIS would have dual seals, instead of the single seals used on the baseline aircraft.

Considering the versatility of the IBIS digital processors for incorporation of built-in test equipment (BITE), task time requirements in the adjustment category should be reduced greatly, just by immediate isolation of problems. Further, FBW control systems are inherently simple and easy to rig. BHTI's previous experience in the flight test of tail rotor FBW controls demonstrated that rigging the FBW controls required about one-eighth the time spent on the mechanical linkage.

5.1.3 Costs

In the following sections, the baseline helicopter cost data are taken from Reference 13, where it was developed in conjunction with the reliability and maintainability analysis of the UH-1N. Operating costs were converted to commercial equivalents.

5.1.3.1. <u>Baseline Helicopter Costs</u>. The base labor rate of $17.29 used in computing scheduled and unscheduled maintenance cost was obtained from an Air Force handbook entitled "Logistic Support Cost Model User's Handbook" dated January 1979. The handbook references AFLCR 173-10, AFLC cost and Planning Factors, as the source of this rate.

Some replacement-part cost data were obtained from the Navy 3M Report M50D4790.A 2707-04 for the periods January - June 1977, July - December 1977, January - June 1978, and July - November 1978. The hydraulic actuator costs were obtained from Hydraulic Research Textron, the maker of the UH-1N actuators. The remaining costs were obtained from the current BHTI Model 212 cost book; the Model 212 and Model 412 are BHTI's commercial equivalent of the UH-1N. Where necessary, a commercial-to-military cost factor of 0.65 was used. This was obtained by comparing the operating cost for the UH-1 series helicopter, based on the Army Field Manual 101-20, dated February 1976 and the 205A-1 operating costs, based on the BHTI pamphlet for commercial operators. The operating cost of the helicopter actuation systems was calculated using military data. For comparison purposes, maintenance costs in a commercial environment are desired. Therefore, all the maintenance costs at the subsystem level were multiplied by a factor of 0.65 to approximate the commercial maintenance environment (described in paragraph 5.1.2.).

Five different cost parameters were calculated. They are listed in the Table 5-6, along with a summary of the results obtained for the baseline helicopter. The costs are expressed in dollars per million flight-hours.

TABLE 5-6. UH-1N CONTROL SYSTEM OPERATING COSTS PER MILLION FLIGHT-HOURS

Scheduled Inspections	$ 3,277,300
Scheduled Replacements	7,388,971
Unscheduled Replacements	7,382,369
Unscheduled Adjustments	1,219,388
TOTAL COST	$19,268,028
INITAL COST	$105,953

Table 5-7 presents the initial costs by subsystems. These include both recurring and nonrecurring costs.

5.1.3.2 Model 412 IBIS Controls Costs. The research and development costs of a program to bench test, whirl test, and wind tunnel test experimental hardware has been the subject of a formal estimating effort at BHTI. The results are shown in Table 5-8.

In the author's opinion, the additional cost of developing and qualifying flightworthy hardware and conducting a thorough flight test program would be approximately twice the amount estimated for the preliminary program detailed in Table 5-8.

In the typical parameteric study fashion, the recurring portion of the initial cost of the IBIS control system would be calculated based on historical data reduced to dollars per pound. Using this method, the recurring cost of unit number 100 would be

$$(407\ \text{lb})\ (\$208/\text{lb}) = \$84{,}656\ \text{(excluding AFCS)}$$

The cost of a full-complement AFCS system as installed on a BHTI AAH was $45,000. The total cost predicted for IBIS on a Model 412 is

$$\$84{,}656 + \$45{,}000 = \$129{,}656$$

However, the author's experience leads to the conclusion that this value is not conservative. But the scope of this program does not provide for detail design data upon which a formal estimating procedure can be based. A practical approach would appear to be the breakdown of the system into subsystems and components and the judgment of experts as to the cost of each item. Toward this end, Table 5-9 was compiled. As an example of the rationalization used in arriving at these costs, the two gear boxes were judged to be, on the basis of part count and complexity, roughly the equivalent of one Model 206L transmission.

TABLE 5-7. UH-1N HELICOPTER ACTUATION SYSTEM OPERATING COSTS (COMMERCIAL ENVIRONMENT)

	Initial Cost[1] (C_I)	Inspection Cost (C_{INSP})	Part Replacement Cost[1]				Unscheduled Subsystem Adjustment Cost[1] (C_A)
			Scheduled		Unscheduled		
			Throwaway (C_{ST})	O/H ($C_{SO/H}$)	Throwaway (C_T)	O/H ($C_{O/H}$)	
	(Form 4)	(Form 3)	(Form 2)	(Form 2)	(Form 4)	(Form 4)	(Form 5)
Cyclic controls	34,845	-	-	-	727,388	1,528,347	234,688
Stick installations	12,746	-	-	-	504,737	-	79,337
Collective controls	18,828	-	-	-	65,782	101,520	71,858
Throttle	7,459	-	-	-	216,062	-	180,243
M/R controls	12,083	-	3,890,520	3,498,451	290,313	3,336,388	393,559
Antitorque controls	17,171	-	-	-	119,917	485,774	235,240
Elevator controls	2,821	-	-	-	6,191	-	24,463
TOTAL	105,953	3,277,300	3,890,520	3,498,451	1,930,340	5,452,029	1,219,388

[1] Express in cost per million (10^6) flight-hours.

TABLE 5-8. M412 IBIS CONTROL RESEARCH AND DEVELOPMENT COSTS

Task	Material	Engineering Hours	Manufacturing Hours
Bench test	$ 300,277	9,572	1,516
Hardware development	1,222,475	21,418	14,487
Whirl test	67,532	3,500	1,158
Wind tunnel test	550	3,500	486
Documentation	-	1,900	-
TOTALS	$1,590,834	39,890	17,647

TABLE 5-9. RECURRING COSTS

Standpipes (2)	$ 1,000
Bearing (2)	500
Gearbox (2)	27,000
Actuators (16)	32,000
Processors/electronics/optics	65,000
Hydraulic systems (4)	12,000
Support/manifold for actuators	4,750
Pitch horns & misc. hardware	5,900
Wiring harnesses	4,800
Sensors	18,000
TOTAL	$170,950

For a direct comparison of the initial cost of the Model 412 IBIS controls and the baseline controls, the nonrecurring cost (approximately $20M) is distributed among 1450 units, as was the case for the baseline (Ref. 13).

Then the initial cost of the Model 412 IBIS controls is $170,950 + $13,793 = $184,743. Some adjustment is still required since the baseline initial cost of $85,961 from Table 5-7 was based on 1979 dollars.

Assuming the 1979/1982 cost differential follows the consumer price index, the fixed cost comparison of the two control systems is

COST IN 1982 DOLLARS

UH-1N	Model 412 IBIS
$85,961 (283.4/217.4) = $112,094	$184,743

Unscheduled maintenance cost due to inherent failures for the Model 412 IBIS is approximately 2.8 times that of the baseline, comparing the ratio of 17,931:6,463, the λ_F from Table 5-5 and the main rotor replacement failure rate from Table 5-2. However, there is another major factor in unscheduled maintenance labor costs in addition to those due to inherent or replacement failures. That factor may be referred to as adjustments. According to Table 5-2, the number of adjustments required on the baseline main rotor controls is 3.5 times the replacement failure rate. Then, using the inherent (replacement) failure rate of the UH-1N as unity, the baseline unscheduled maintenance failure rate is 4.5.

Now, consider that the Model 412 IBIS has virtually eliminated the rotating controls, labeled main rotor controls in Table 5-2. That is to say that the swashplate, scissors, tubes, and joints (more than half of the adjustments) have been eliminated. Also consider that blade tracking is automatic in the 412 IBIS, and that rigging is an order-of-magnitude less demanding with FBW. Therefore it's not unreasonable to conclude that the unscheduled incidents for the 412 IBIS would be 2.8 + 1/2 (3.5) or 4.55 units, as compared to 4.5 units for the baseline.

No effort has been made to calculate the cost of replacement parts for the Model 412 IBIS.

5.1.4 Drag Reduction

The controls and mast between the rotor and fuselage of a Model 412 helicopter cause significant drag in cruise flight. Placing the flight controls on the rotor hub with proper fairing, eliminating the swashplate and associated linkage, and fairing the mast below the rotor will reduce rotor drag approximately 40 percent. This figure results from an analysis performed on wind-tunnel data contained in Reference 14. A comparison of conventional and IBIS 412 drag in shown in Table 5-10.

TABLE 5-10. CONTROL SYSTEM DRAG COMPARISON - EQUIVALENT FLAT PLATE DRAG

Conventional 412		IBIS 412	
Hub and blade grips	1.74 ft^2	Hub and blade grips + fairing	2.35 ft^2
Pitch links	1.23		-
Mast	1.11	Mast Streamlined with Fairing	0.56
Swashplate, support, etc.	0.83		-
	4.91 ft^2		2.91 ft^2

5.1.5 Weights

The following paragraphs report the weights of the baseline Model 412 helicopter controls, and the weights of the IBIS controls installed on the same helicopter airframe. For purposes of a clear and direct comparison, the first two subparagraphs present only the weights of flight-critical components of the main rotor control components, since the IBIS was intended specifically for actuation of large rotors and is not suitable for application to the tail rotor or elevator.

The impact of active control technology on the weights of the tail rotor and elevator is discussed in subsequent subparagraphs. Also, weight factors associated with cockpit controllers and displays are discussed.

5.1.5.1 Baseline Helicopter Main Rotor Control Weights. The Model 412 main rotor flight control weights are shown in Table 5-11. The rotating controls include the swashplate and all components between it and the rotor blades. The nonrotating controls include the hydraulic boost actuators and all of the mechanical linkage back to the interconnect between the pilot and copilot controls. The interconnect and sticks are not included.

TABLE 5-11. MODEL 412 MAIN ROTOR CONTROL SYSTEM WEIGHTS

Rotating controls	122.5 lb
Nonrotating controls	114.9
Hydraulics (2 systems)	92.8
AFCS[1]	53.9
TOTAL	384.1 lb

[1] Rate gyros and their installations were purposely omitted from this weight.

5.1.5.2. Weight Impact of Active Controls on the Cockpit. Side-arm controllers are in use in both fixed-wing aircraft and helicopters. A force-type (modified to force/limited displacement) stick is in production on the F-16, and a displacement type side-arm cyclic stick has been used in the AH-1 Cobra at the copilot station since 1969. The force or force/limited displacement type side-arm controller is possible only with FBW or FBO.

This type of stick, if used on the IBIS control system, would result in about 20 pounds of weight savings over the mechanical equivalent (Ref. 15).

5.1.5.3. Weight Impact of Active Controls on the Tail Rotor. Reference 16 documents the weight savings of a fail/operate FBW (power by wire) tail rotor control. Approximately 6.5 pounds are saved by use of such a tail rotor control.

5.1.6 Benefits of Active Control for Deicing Rotor Blades

Several vibratory deicing concepts were evaluated in Reference 17. These include gearbox shakers, shakers buried in the blades, and hub shakers. Additionally, high-frequency cyclic pitch has been suggested as a possible means of shedding ice from main rotor blades.

Here, a change in lift, due to cyclic pitch change, excites the blade at the natural frequency of a blade out-of-plane bending mode. From Reference 1, this change in lift, ΔL, is analogous to the force that is applied to the rotor:

$$F = \int_0^R \Delta L \, dr = \int_0^R \frac{\rho c a_o (\Delta\alpha) \, \Omega^2 r^2 dr}{2} \qquad (8)$$

where

ρ = air density
c = rotor chord
a_o = airfoil section lift-curve slope
Ω = rotor angular velocity
$\Delta\alpha$ = change in section angle of attack
r = radius to airfoil section

The work done by this force on a given mode at its natural frequency is

$$\frac{\rho c a_o (\Delta\alpha) \, \Omega^2 \int_0^R r^2 \, MS \, dr}{2 \, GI_n} = 2\zeta W_n \dot{\delta} \qquad (9)$$

where

MS = mode shape out-of-plane displacement
GI_n = generalized inertia
ξ = damping factor
W_n = natural frequency
δ = generalized coordinate associated with the mode

Rearranging the terms gives

$$\Delta\alpha = \frac{4\zeta \omega_n^2 \, GI_n}{\rho c a_o \, \Omega^2 \int_0^R r^2 \, MS \, dr} \qquad (10)$$

Assuming a damping factor of 0.02 to represent the combined structural and aerodynamic damping for the high-frequency modes, and using the strain requirement of 0.003 in/in from Reference 17, the Myklestad program (Ref. 18) was used to determine the essential parameters for blades of several rotor systems. The results are shown in Table 5-12.

TABLE 5-12. CYCLIC PITCH REQUIREMENTS FOR ICE SHEDDING

Rotor System	Cyclic Pitch Frequency (cpm)	Cyclic Pitch Amplitude (±deg)
UH-1	2569 (rotating) 2245 (fixed)	3.687
AH-1	2571 (rotating) 2247 (fixed)	1.178
CH-47	1888 (rotating) 1638 (fixed)	1.621
OH-58	2694 (rotating) 2341 (fixed)	1.284

In the case of the UH-1, the requirement of ±3.687° of pitch change at 42.8 Hz was completely out of reason at the time the work was done. However, for the BHTI OH-58, ±1.284° of blade pitch change at 44.9 Hz appeared less formidable.

For the present assessment, the same procedure is applied to the BHTI Model 412 rotor. The strain level was raised for conservatism. The results are that the third collective out-of-plane mode, at a natural frequency of 4.483/rev (4.483 x 314 cpm = 1408 cpm) or 23.47 Hz can be excited sufficiently by ±0.68° of blade pitch change to cause ice shedding (0.0004 in/in strain at the icebond).

Should it be necessary to excite another mode to clear ice from nodes associated with this third collective out-of-plane mode, the third cyclic out-of-plane mode at 4.42/rev can be excited by ±1.82° of blade pitch change.

Table 5-13 contains a tabulation of parameters used in these calculations, as well as data for the second collective and second cyclic modes. For both of these modes, the strain required to shed ice was assumed to be 0.0004 in/in, as in the cases of the higher modes.

TABLE 5-13. MODEL 412 MAIN ROTOR EXCITATION FOR ICE SHEDDING

	2nd Col	3rd Col	2nd Cyc	3rd Cyc
ω_n (Hz)	85.79	147.2	85.2	145.3
δ	1.568	0.651	2.158	1.242
GI	0.0869	0.0585	0.0775	0.0682
(in)	15.9	15.3	15.9	15.9
a_o (/deg)	0.107	0.107	0.107	0.107
Ω^2 $[(\text{rad/s})^2]$	1081.0	1081.0	1081.0	1081.0
$\int_0^R r^2 MS\, dr$	488260.0	482980.0	618470.0	-373850.0
$\Delta\alpha$ (deg)	±1.04	±0.68	±0.99	±1.82

Since the levels of excitation required to shed ice may be less in magnitude than that required for vibration reduction, one can rationalize that deicing can be essentially free, once the high frequency actuation capability is installed for vibration reduction.

5.2 RELATED COCKPIT TECHNOLOGY

A large number of civil missions were investigated during this study and their special needs examined. Twelve of these missions are listed in Table 5-14, along with the visual and voiced (or audio) displays, made possible through the use of computer technology, that meet the requirements of the special needs. The table is set up in the form of a matrix in which checkmarks identify those displays that satisfy the needs of a particular mission. Where appropriate, details of the needs are provided.

All missions have basic phases they share: mission planning, preflight checks, takeoff, etc. These are shown in Figure 5-5 in block diagram form as the first level of mission breakdown. The unique part of most missions is block 7.0, identified as "Perform Mission." Further analysis, at Level 2, may be seen in Figure 5-6 for a Forestry and Logging mission. Seven blocks list the maneuvers required to perform this mission. Similar, if not identical, maneuvers are required for the Cargo and Construction

TABLE 5-14. MATRIX OF CIVIL MISSIONS WITH COCKPIT DISPLAYS AND CONTROLS NEEDED TO IMPROVE MISSION EFFECTIVENESS[1]

	Visual Displays							Voiced Displays		
Missions	HMD or HUD	Night Vision	System Operating Predictors	Fuel Conservation Data	Aircraft Performance Calculations	Local Area Nav Display	Hover Display	Caution/Warning Date and Checklists	Flight Director	Flight Parameter Monitor
Corporate	√N LA IFR	√	√ F	√	√	OFF A NRA		√	√LA	√
Schedule air transport	√N IFR LA	√	√ F	√	√			√	√PH LA	√
Resource	√N A/PMC	√	√ F	√	√	OFF A	√	√		√
Public service										
Rescue	√PH A/PMC	√	√F	√	√	OFF A NRA	√	√	√PH LA	√
Police	√A/PMC	√	√F	√	√	OFF A NRA	√	√		√
Fire	√PH A/PMC	√	√F	√	√	OFF A NRA	√	√	√PH LA	√
Ambulance	√A/PMC	√	√F	√	√			√		√
Disaster control	√A/PMC	√	√F	√	√		√	√		√
Cargo & construction	√A/PMC	√	√F	√	√		√	√	√PH	√

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TABLE 5-14. (Concluded)

	Visual Displays							Voiced Displays		
Missions	HMD or HUD	Night Vision	System Operating Predictors	Fuel Conservation Data	Aircraft Performance Calculations	Local Area Nav Display	Hover Display	Caution/Warning Date and Checklists	Flight Director	Flight Parameter Monitor
Forestry & logging	√A/PMC	√	√F	√	√		√	√	√PH	√
Agriculture	√A/PMC		√F		√			√	√ Direction Control	√
Media support	√N, LA IFR A/PMC	√	√	√	√		√		√PH	√
Off-shore transport	√N, LA IFR A/PMC	√	√	√	√		√	√	√LA	√

[1] Legend of detail of needs:

PH = Precision hover
A = Attitude control
PMC = Partial instrument meteorologies conditions
OFF A = Off airways
LA = Landing approach
F = Reduce fatigue
NRA = No radio aids nav
N = Night
I = Improve monitoring
√ = Item needed.

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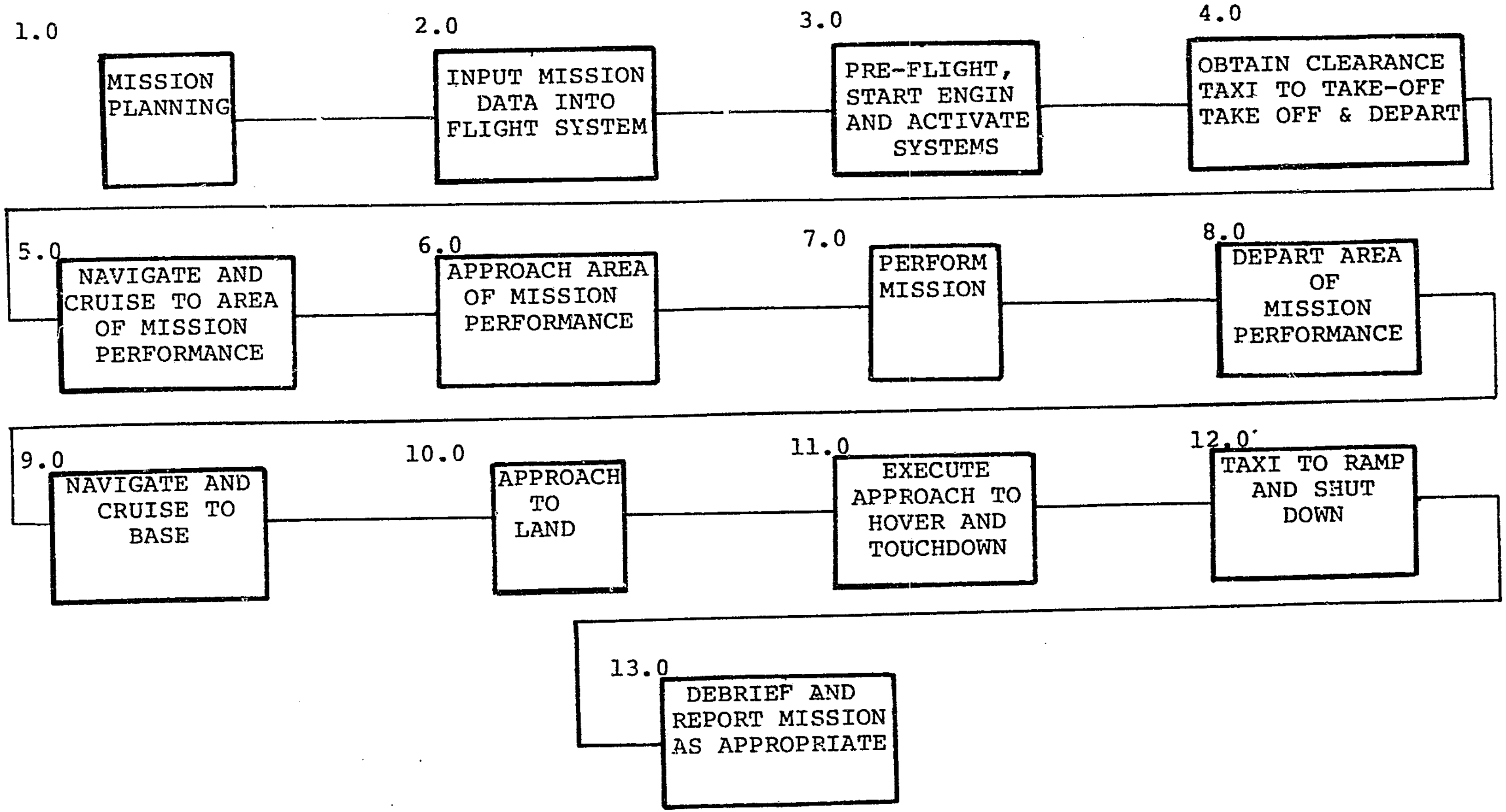

Figure 5-5. Level 1 breakdown for a general mission.

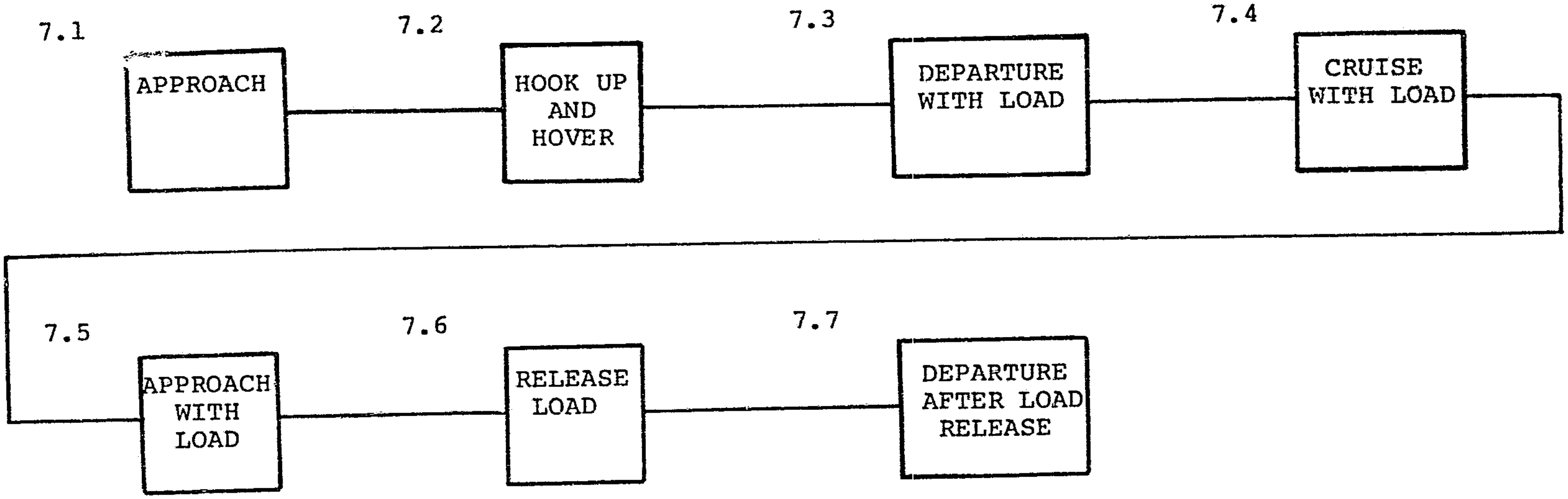

Figure 5-6. Level 2 breakdown of "perform mission" segment of cargo and construction missions.

mission. This mission was one of the more representative and more difficult of all the civil missions addressed. It has been taken to Level 3 and beyond in Table 5-15. The handling of the external load has been detailed in terms of a three-man crew: pilot, copilot, and crew chief.

A close examination of Table 5-15 reveals that maneuvering problems extend throughout the mission and require precision hover, close-in navigation and approach. A study by Franks, et al. (Ref. 19) investigated an identical mission. The mission segments were analyzed by expert pilots who had flown the mission. Data on visual and manual pilot workload were developed. Figure 5-7 represents the pilot workload. Results indicate that the highest workloads occur during load hookup and release.

Implications for design from this study indicate a need for the following:

a. Improved external vision and night vision.

b. Data on external load (weight).

c. Precise location of load acquisition and drop zone.

d. Operating performance data for fuel conservation.

e. Automatic hover control.

f. Data redundancy, i.e., audio prompting for position and approach.

g. Map display.

h. HUD or helmet/head-mounted display.

From interviews with active pilots operating helicopters performing these and other civil missions, it was found that all pilots want designs that will provide

a. Improved vision.

b. Improved capability at night and in marginal visibility conditions.

c. Improved data on aircraft performance and fuel conservation.

d. Reduced pilot workload and fatigue.

TABLE 5-15. FLIGHT CREW LEVEL-3 TASK ANALYSIS FOR CARGO AND CONSTRUCTION MISSIONS (EXTERNAL LOADS)

Level	Pilot Tasks	Copilot Tasks	Crew Chief Tasks
7.1	<u>APPROACH</u>		
7.1.1	<u>Initiate Descent</u>		
	Receive prelanding check complete from copilot.	Execute prelanding check and notify pilot when complete.	Scan pickup zone (PZ) obstructions and other hazards.
	Reduce thrust and initiate descent.	Monitor instruments and scan PZ for hazards.	<u>Note</u>: CH47 will normally have two crew chiefs for external load operations.
	Scan PZ and locate ground signalman.		
7.1.2	<u>Descent</u>		
	Make control corrections as required to maintain selected approach angle.	Continue to monitor.	Continue to monitor PZ for hazards.
	Make descent corrections as required to follow ground signalman.		
	Monitor hazard messages from other crewmembers.		
7.1.3	<u>Terminate Descent</u>		
	Increase thrust and decrease descent rate, reducing spped so as to terminate descent at a hover.		

TABLE 5-15. (Continued)

Level	Pilot Tasks	Copilot Tasks	Crew Chief Tasks
7.1.3	Terminate Descent (continued) Maintain hover downward of load and prepare to follow ground signals.		
7.2	HOOK-UP		
7.2.1	Maneuver Overload		
	Adjust hover height to clear load.	Scan load for proper rigging.	Continue to monitor PZ for obstacles and advise rest of crew.
	Hover toward load following ground signalman and notify load passes under nose.	Continue to monitor instruments for proper indication.	Note: CH-47 crew chief will at time assume a position aft of the rescue hatch so that he can view both the hook and the load. From this time he will provide verbal directions to the pilot.
	Received "Hook-Armed" from copilot.	Place hook arm switch to armed position and advise pilot.	When load is in sight, give verbal directions to pilot as necessary and notify pilot. (CH-47)
	Hover toward load following ground signalman and notify crew when load passes.	Continue to monitor instruments for proper indication.	Continue to monitor PZ for obstacles. (UH-1 and UH-60)

TABLE 5-15. (Continued)

Level	Pilot Tasks	Copilot Tasks	Crew Chief Tasks
7.2.1	<u>Maneuver Overload</u> (Continued)		
	Receive directions from crew chief. (CH-47)	Place pilot external radio off at ICS box and inform pilot.	Notify pilot when hook is overloaded.
	Continue to monitor either ground signalman or crew chief to place hook over the load.		
7.2.2	<u>Attach Sling to Hook</u>		
	Remain at hover over load.	Continue to monitor instruments and scan PZ for obstacles.	Monitor ground crew and gives pilot directions to remain centered over load. (CH-47)
	Receive "Load Hook" signal from either ground signalman or crew chief.		Inform pilot when load is hooked. <u>Note</u>: Crew chief may hook up the load from inside the aircraft by use of the loading pole. (CH-47)
7.2.3	<u>Raise Load Off Ground</u>		
	Receive signal to raise to tighten sling straps from either ground signalman or flight crew chief.	Scan engine instruments for normal.	Inform pilot to tighten strap. (CH-47)

TABLE 5-15. (Continued)

Level	Pilot Tasks	Copilot Tasks	Crew Chief Tasks
7.2.3.	Raise Load Off Ground (Continued)		
	Increase torque to raise helicopter until slips/straps are tight.	Monitor engine for performance limits.	Inform pilot when load is 5 feet off gound. (CH-47)
	Apply additional torque to raise load 5 feet off ground and receive "5 ft" signal.		
7.2.4	Prepare for Takeoff		
	Continue to hover with load off the ground.	Perform pre-takeoff checklist and notify pilot when complete.	Scan load for proper rigging and ride.
	Receive pre-takeoff checklist complete and initiate takeoff.	Monitor engine instruments for performance.	Scan takeoff lane for obstacle clearnace.
7.3	DEPARTURE WITH LOAD		
7.3.1	Initiate Climb		
	Increase thrust/collective and start coordinated climb.	Monitor instruments for performance.	Scan departure zone for obstacles.
	Establish climb angle to clear obstacles at maximum allowable power.		
7.3.2	Climb Out		
	Continue climb at maximum power until clear of obstacles, then reduce to normal.	"Safe" hook of flight is above 300 feet and notify pilot.	Monitor load for obstacles clearance and oscillation. (CH-47 UH-60)

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TABLE 5-15. (Continued)

Level	Pilot Tasks	Copilot Tasks	Crew Chief Tasks
7.3.2	Climb Out (Continued)		
	Climb power.		
	Receive "Hook Safe" call for cockpit.		
7.3.3	Initiate Level-off		
	Reduce thrust and accelerate to desired cruise at desired altitude.	Monitor instruments for proper reading	Monitor load for oscillation. (CH-47 and UH-60)
7.4	CRUISE (Level 3 detail not appropriate).		
7.5	APPROACH WITH LOAD		
7.5.1	Initiate Descent		
	Receive prelanding check from copilot.	Complete prelanding check and notify pilot.	Scan approach for obstacles and check load for oscillations. (CH-47)
	Decrease thrust and initiate approach.	Monitor instruments for proper indications.	
7.5.2	Descent		
	Adjust power and make control corrections as required to maintain selected approach angle.	"Arm" hook and notify pilot.	Continue to scan DZ for obstacles.

TABLE 5-15. (Continued)

Level	Pilot Tasks	Copilot Tasks	Crew Chief Tasks
7.5.2	Descent (Continued)		
	Receive "Hook Armed" signal from copilot.		
	Scan DZ for ground signalman and make coorections as required.		
7.5.3	Terminate Descent		
	Increase thrust and decrease descent rate to terminate at a hover with load 15 feet above ground.	Monitor engine instruments for performance limitations.	Continue to scan DZ for obstacles.
	Maintain hover downwind of load and prepare to follow ground signals.		
7.6	RELEASE LOAD		
7.6.1	Maneuver to Release Point		
	Ajust hover height to maintain load off ground.	Continue to monitor instruments.	Continue to scan DZ for obstacles.
	Hover towards drop point following round signalman.	Scan DZ for obstacles.	Direct pilot to place load over drop point. (CH-47)
	Monitor ground signalman to place load over drop point.		
	Crew chief directs pilot over drop point. (CH-47)		

TABLE 5-15. (Continued)

Level	Pilot Tasks	Copilot Tasks	Crew Chief Tasks
7.6.2	Lower Load to Ground		
	Hold poistion over drop point.	Monitor instruments for proper indication.	Continue to scan DZ for obstacles.
	Reduce thrust and start lowering load as directed by either ground signalman or crew chief.		Direct pilot to lower load to ground. (CH-47)
7.6.3	Release Load from Hook		
	As load touches ground, continue descent to obtain slack in the slings.	Monitor engine instrument for normal operations.	Direct pilot to descend and notify when slack in sling. (CH-47)
	Receive "Load Released" signal from either ground signalman or crew chief.		Notify pilot when load is released. (CH-47)
7.6.4	Prepare for Takeoff		
	Hover to takeoff point.	Accomplish pre-takeoff check and notify pilot when complete.	Scan DZ for obstacles.
	Receive pre-takeoff check list complete signal from copilot.		
7.7	DEPARTURE AFTER LOAD RESLEASE		
7.7.1	Initiate Climb		
	Increase thrust/collective and start coordinating climb.	Monitor instruments for performance limits.	Scan departure path for obstacles.

TABLE 5-15. (Concluded)

Level	Pilot Tasks	Copilot Tasks	Crew Chief Tasks
7.7.1	Establish climb angle to clear obstacles.		
7.7.2	Climb-Out Continue climb until clear of all obstacles.		
7.7.3	Initiate Level-off Reduce thrust and accelerate to desired speed at desired altitude.	Monitor instrument for normal operations.	

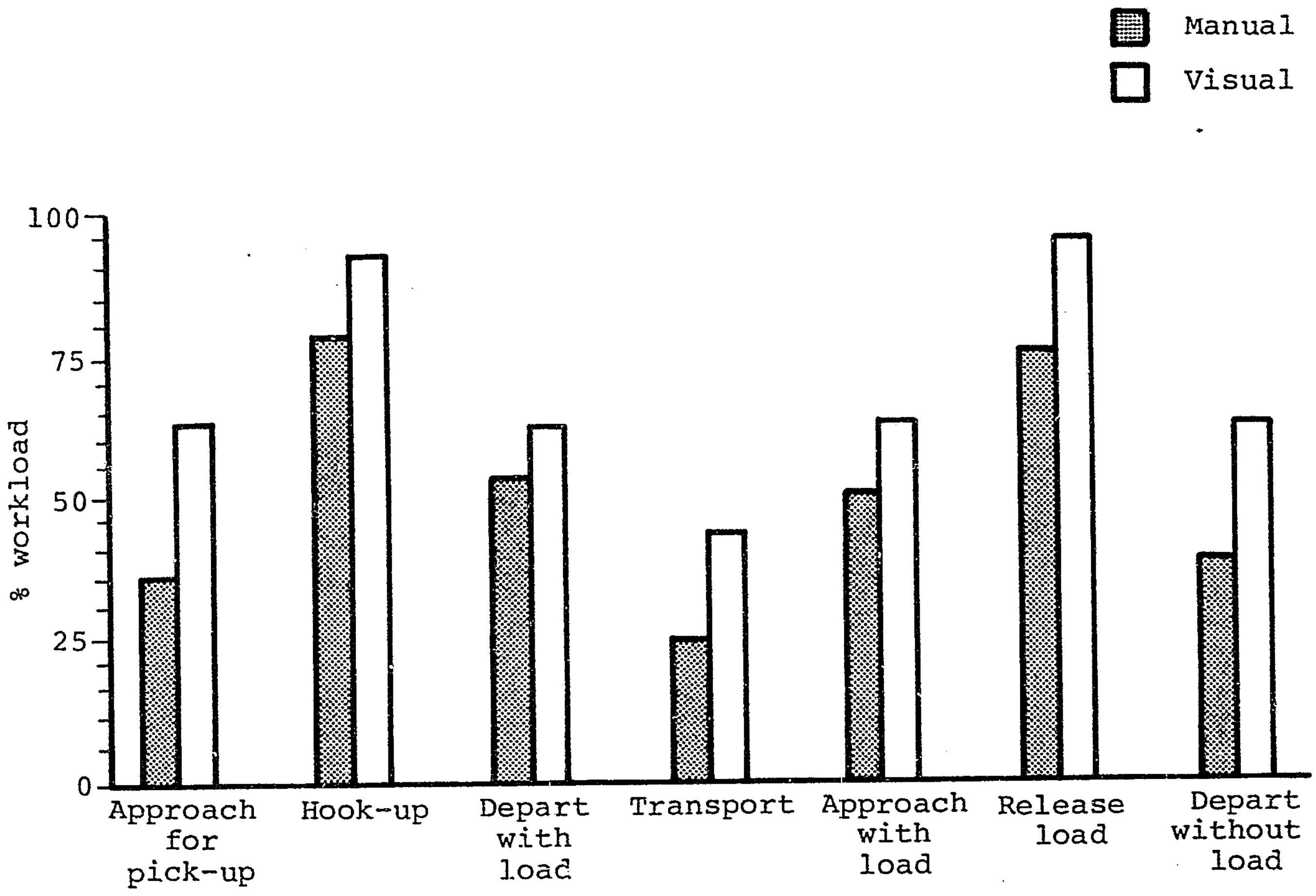

Figure 5-7. Baseline workload of a slingload mission.

Future display formats will optimize pictorical displays, based to a large extent on an experimental research helicopter system developed under Tri-Services funding. This program utilized the concept of pictorial displays that would permit operation under IFR equal to that under VFR. Successful flight tests with these displays were made in the middle 1960s (Refs. 20 and 21). This concept of pictorial flight displays has been reemphasized by NASA Ames (Ref. 22).

Data from the above studies led to development of RCT Panel 3, which is discussed in Section 4 and shown in Figure 4-9. The advanced display concepts in this panel use integrated cockpit techniques and employ multifunction displays, data input panels, and digital maps.

Voiced displays and a micro-HUD augment the cockpit control and display systems. The controls selected for this cockpit include a console-mounted, displacement-activiated collective, conventional foot pedals, and a two-axis, force-activated, side-arm cyclic. the control system includes stabilization and heading, attitude, and hover-hold modes.

Workload estimates were approximated for the RCT cockpit, using an activity index of crew performance. To do this three experienced helicopter pilots, familiar with integrated displays, estimated crew activity at three levels: continuous, intermittent, and a one-time action. To represent increasing demands on performance ability, rank scores of 3, 2, and 1 were assigned, respectively, to continuous, intermittent, and one-time action. Activity estimates were made for each task represented at the Level 3 task analysis. Each pilot ranked each task using each of the three RCT panels as represented in Figure 4-8.

The activity level for the conventional, or baseline, panel (Panel 1) was assigned the workload percentage value taken from Reference 19, a U.S. Army AVRADCOM report. These workload values may be seen in Figure 5-7. The estimated workload values for RCT Panels 1, 2, and 3 may be seen in Table 5-16.

Comparing these workload values with the baseline permits an estimate of workload improvement as a function of integrating the cockpit.

The estimated improvement realized for the Panel 3 design may be seen in Figure 5-8. Estimates are provided for both visual and control or manual activities. High improvement may be observed for control activity. This is a result of the inclusion of a hover hold and stabilization system.

TABLE 5-16. LEVEL THREE WORKLOAD ESTIMATES FOR RCT PANELS

Level	Parameter	Panel 1(Baseline)		Panel 2 (Interim)		Panel 3(Advanced)	
		Displays	Controls	Displays	Controls	Displays	Controls
7.1 Approach	a. Mean activity index est.	3.0	3.0	2.8	2.2	2.6	1.4
	b. Workload (from Franks)	65%	35%				
	c. Estimated workload[1]			61%	26%	56%	16%
7.2 Hook-up	a. Mean activity index est.	3.0	3.0	3.0	2.8	3.0	1.8
	b. Workload (from Franks)	90%	80%				
	c. Estimated workload[1]			90%	76%	90%	49%
7.3 Departure w/load	a. Mean activity index est.	2.8	2.6	2.2	2.6	1.8	1.2
	b. Workload (from Franks)	60%	55%				
	c. Estimated workload[1]			47%	55%	38%	25%
7.4 Cruise	a. Mean activity index est.	2.0	2.0	2.0	1.0	1.0	1.0
	b. Workload (from Franks)	40%	25%				
	c. Estimated workload[1]			40%	12%	20%	12%
7.5 Approach w/load	a. Mean activity index est.	2.8	2.8	2.4	2.2	1.6	1.2
	b. Workload (from Franks)	60%	50%				
	c. Estimated workload[1]			51%	39%	34%	21%
7.6 Release load	a. Mean activity index est.	3.0	3.0	2.4	2.0	2.4	1.1
	b. Workload (from Franks)	95%	75%				
	c. Estimated workload[1]			76%	50%	76%	27%
7.7 Departure aft. load release	a. Mean activity index est.	2.5	2.2	2.2	1.5	1.7	1.0
	b. Workload (from Franks)	60%	40%				
	c. Estimated workload[1]			52%	27%	41%	18%

[1] Estimated workload

$$= \frac{\text{Panel 2 (or 3) mean activity index}}{\text{Panel 1 (baseline) mean activity index}} \times \text{Panel 1 workload (from Franks)}$$

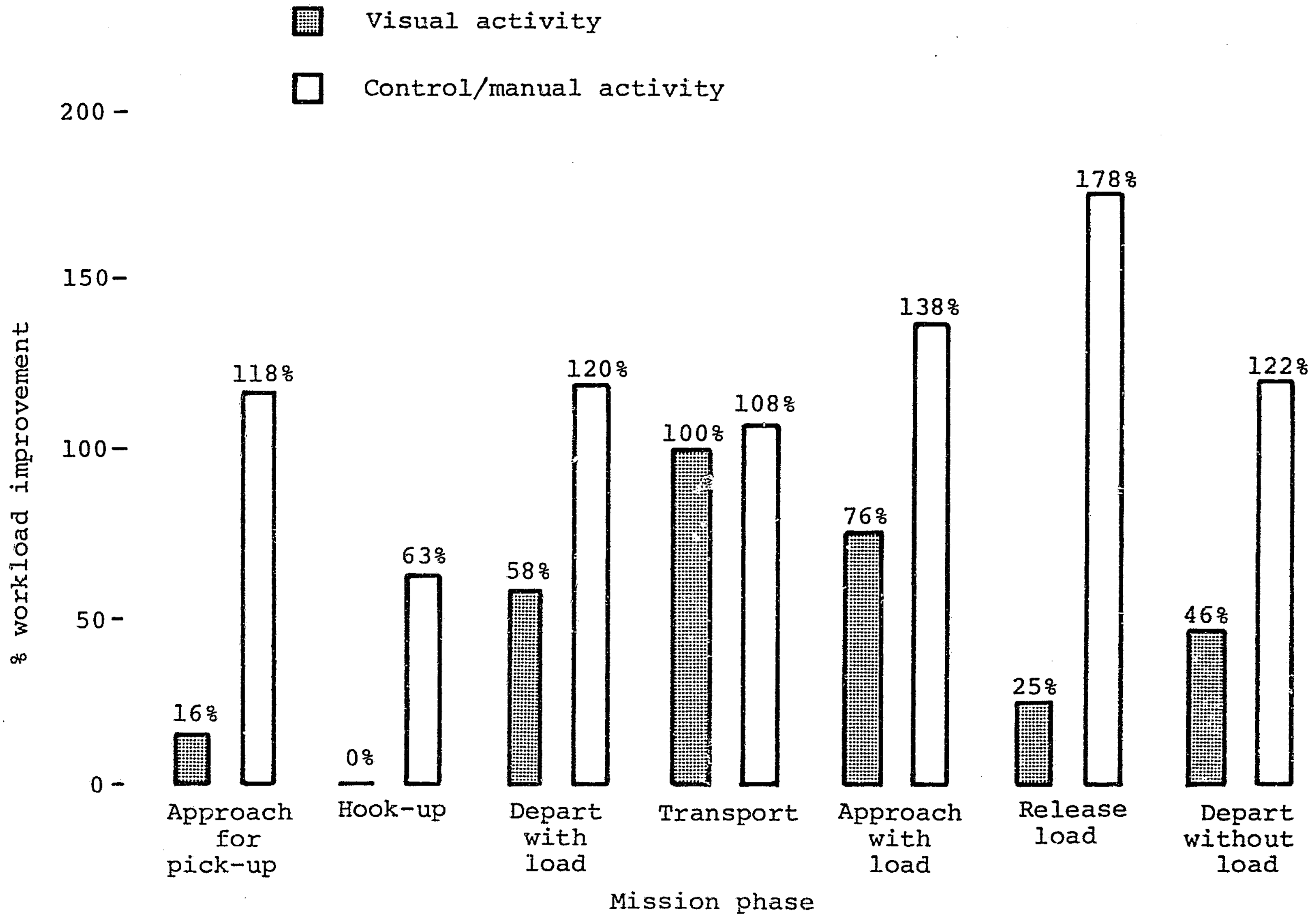

Figure 5-8. Percent improvement in pilot activity of RCT cockpit #3 over baseline.

6. RECOMMENDED NASA & FAA RESEARCH OPTIONS

The specific recommendations made in this section are offered only after very serious consideration of whether (a) such research and development (R&D) would be accomplished by private industry sponsorship as a matter of course, (b) existing programs by other agencies might produce the same or similar results, (c) technical risks are manageable, and (d) potential payoffs outweigh R&D and recurring costs.

6.1 ROTOR CONTROL BY ACTUATORS IN THE ROTATING FRAME

It is recommended that NASA sponsor, in coordination with the Applied Technology Laboratory (AVRADCOM), Fort Eustis, Virginia, a program to foster the development of the technology base required to achieve rotor control in the rotating frame.

Some researchers of multicyclic rotor control systems agree that individual blade control will be required if all of the potential benefits of multicyclic control are to be realized. Kretz, in Reference 23, goes so far as to state, "In order to substantiate all benefits that active control can bring to helicopters, we must satisfy at least two conditions essential to this technique:

- Extremely fast response actuators, having satisfactory response up to at least 30 Hz.
- Location of actuators in the rotating part of the rotor."

Difficulties involved in accomplishing HHC with actuators in the fixed frame have been highlighted recently in a still active experimental program aimed at flight testing HHC on an OH-6 helicopter (see Ref. 24). The major difficulty is manifested by loss of command signal (motion) between the actuator in the fixed frame and the blade in the rotating frame.

Presently, work is underway to reduce slop and increase the stiffness of the intermediate fixed and rotating controls.

A program to systematically develop the concept of rotor control by actuators in the rotating frame has potential benefits comparable to those realized from the introduction of turbine engines and composite materials to helicopters.

Key elements of a program to accomplish the recommended research and development are:

a. Qualification of highly reliable optical sliprings.

b. Qualification of actuators capable of motion at frequencies in excess of 30 Hz.

c. Development of experimental hardware adaptable to an existing rotor, such as the Model 412.

d. Development of a fly-by-wire/fly-by-optics architecture with a proven force-fight and failure management scheme.

e. Implementation of successful control optimization algorithms.

f. Bench or "Iron-Bird" tests.

g. Whirl and/or wind tunnel tests.

h. Design, fabrication, and flight test of flightworthy hardware.

Except for the first and last elements, such a program has been the subject of a formal estimating procedure at BHTI. The following is an estimate of material costs and manhours required to accomplish bench, whirl, and wind tunnel tests of the Model 412 IBIS control system:

	Material	Engineering Man-hours	Manufacturing Man-hours
Bench test	300,277	9,572	1,516
Whirl test	1,290,007	24,918	19,145
Tunnel test	500	3,500	486

The bench test consists of a Model 412 rotor hub to be used as the test stand, one blade set (4) of IBIS control actuators, and one each of IBIS hydraulic and electrical power supplies to be used for one of the IBIS control actuators. Bench power is used for the remaining three IBIS control actuators, and three lab actuators are attached to the controlled blade to simulate pitch, flap, and lead-lag loads and motion.

The whirl test will use a Model 412 rotor with the total IBIS control installed. The wind tunnel test will use the whirl test rotor.

Schedules for the bench test and the whirl/wind tunnel tests are presented in Figures 6-1 and 6-2.

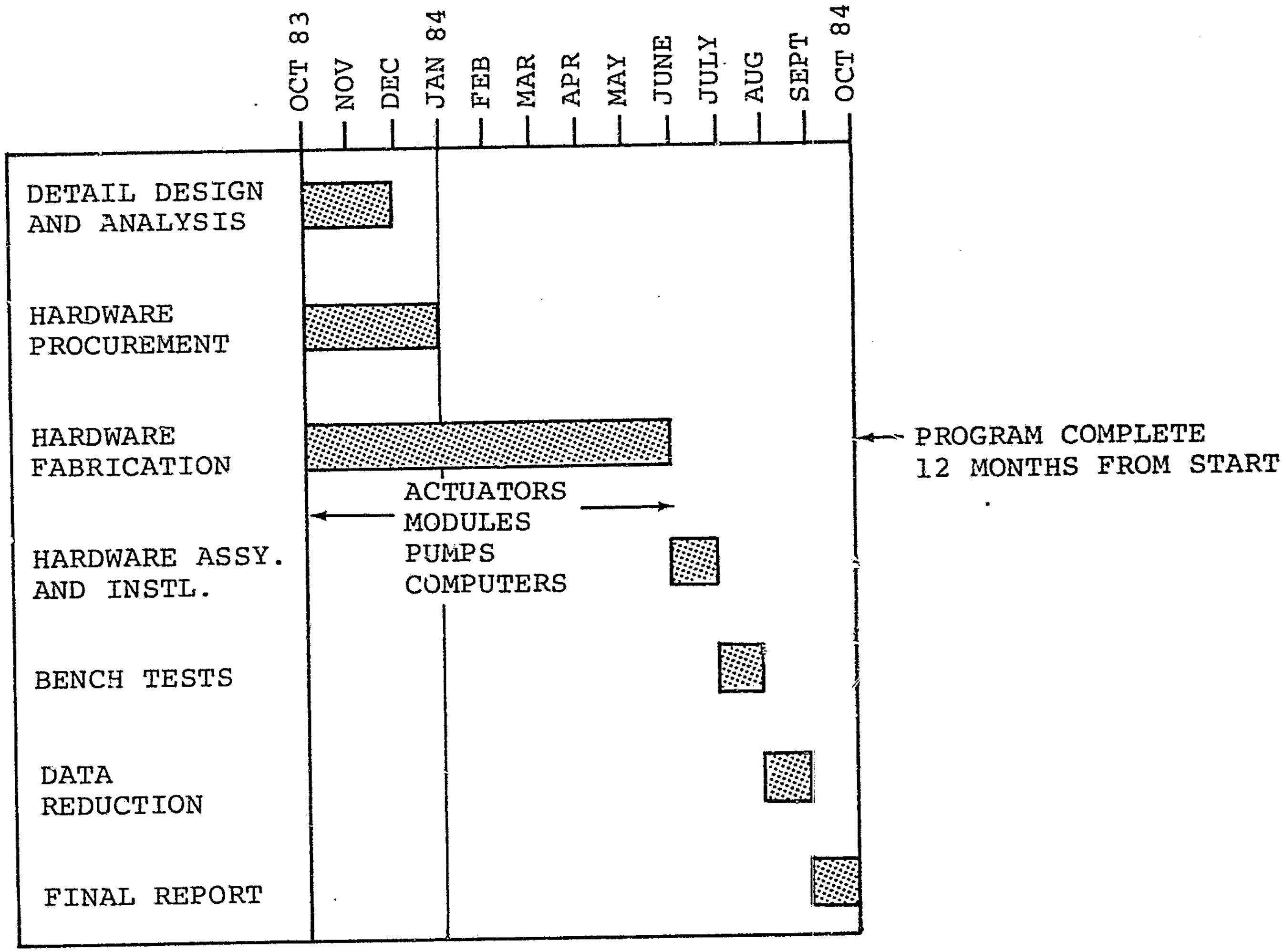

Figure 6-1. Bench test schedule.

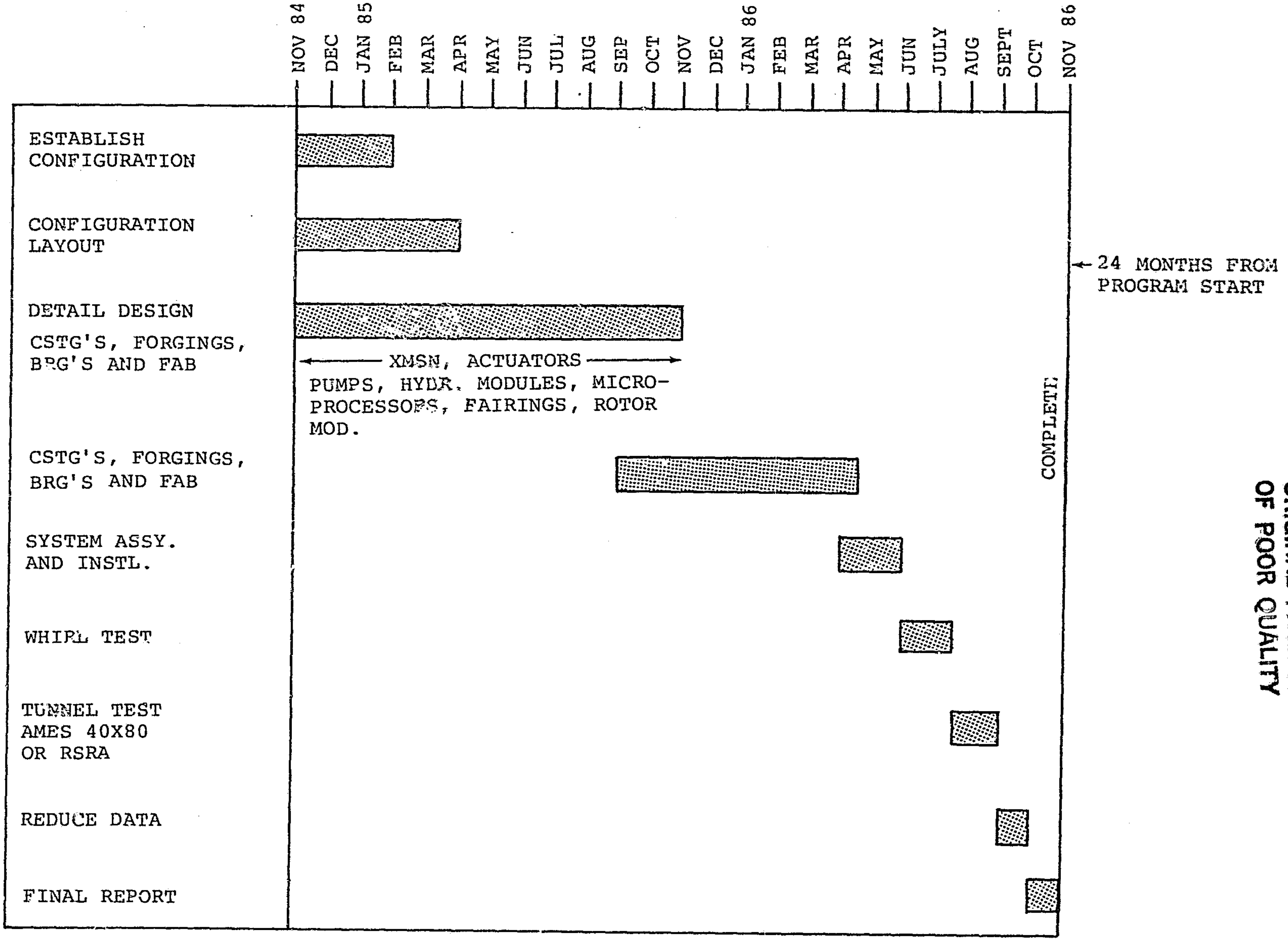

Figure 6-7 Whirl/wind-tunnel test schedule.

6.2 NOISE REDUCTION THROUGH ACTIVE CONTROL

It is recommended that the FAA, in coordination with NASA, sponsor the development of active controls aimed at improving the noise signature of rotorcraft in the partial power descent segment of the mission. Potential benefits of this type of active controls are discussed in subsequent paragraphs.

For the suggested program to succeed, it must be acknowledged from the beginning that any noise certification requirements regarding the glide slope, airspeed, and rotor speed in the approach mode will have to be altered.

It is generally agreed that rotor noise is a major concern currently facing rotorcraft manufacturers. Work reported in Reference 25 and other sources have shown that rotor blades intersecting the tip vortex caused by passage of the preceding blade create an impulsive slapping sound. This impulsive noise is most objectionable in the descent segment of the flight mission because ground observers are typically closer to the helicopter at this point than in any other flight mode.

It has been shown that rotor noise during approach can be minimized by certain flight path control procedures. This is depicted in Figure 6-3a, a plot of rate-of-descent vs airspeed that delineates two zones, one inside the other, where high noise levels occur. The inner zone has the highest noise intensity. Figure 6-3b represents the noise footprint resulting from an arbitrary constant glide slope approach, while Figure 6-3c represents the reduced noise footprint resulting from the alternate flight path shown in Figure 6-3a.

Highly skilled pilots have little difficulty in flying the alternate approach procedures. Up to this point, no active control is required; however, if variable tip speed (rotor rpm) is considered, further reduction in noise footprint can be made, or the zones of high-intensity noise could be shrunk, allowing a less severe glide slope to be flown in the alternate approach procedures.

Since the descent requires little power and since the time duration is short, fuel efficiency is not a major concern here. Then, rotor rpm could be reduced by 15 or 20 percent, depending on rotor dynamics, until such time as hover power is required.

Active control, in the form of a straightforward nonlinear optimization routine with appropriate constraints, coupled to the AFCS and a digital engine fuel control, should reduce greatly the size of the high-intensity noise zone, if not eliminate the slapping noise.

C-2

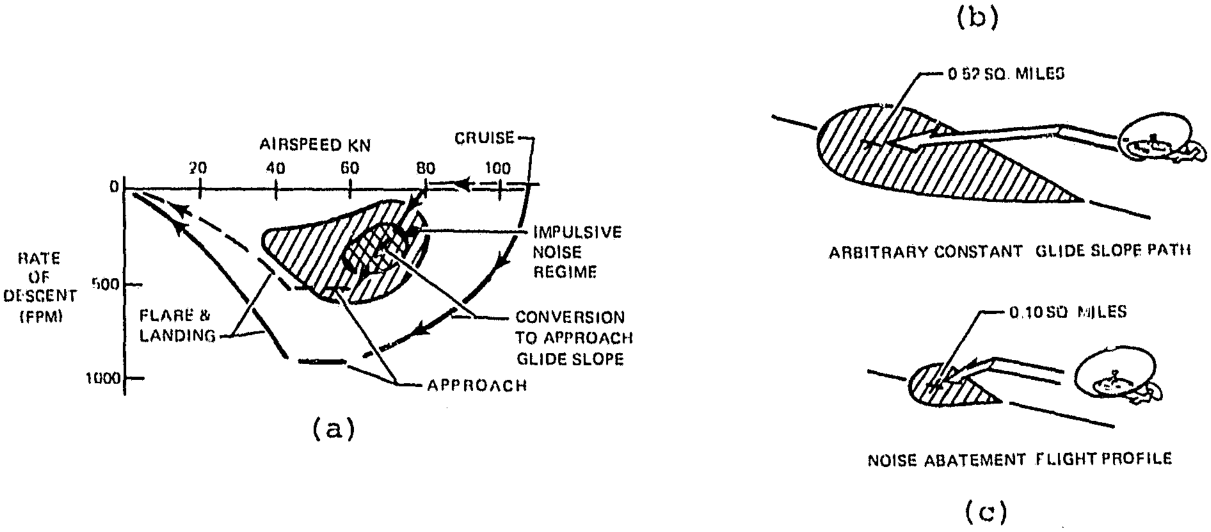

Figure 6-3. Effect of flight path control on noise footprint.

Key elements of a program to eliminate impulse noise during approach and reduce the noise footprint by more than 80 percent are presented below:

a. Establish the descent rate and airspeed corridor in combination with rotor speed, for a given helicopter, to achieve the objective.

b. Evaluate rotor dynamics and stability under the established operating conditions. Assess other possible risks.

c. Define new hardware and software, and aircraft modifications.

d. Determine costs.

e. Review costs vs benefits.

f. Design, fabricate, and test the concept. Evaluate impulsive noise corridors by measuring noise both in the rotorcraft and on the ground. Develop graphical representations of the noise footprint.

g. Publish a design guide and determine applicability to certification standards.

No special facilities are required for this program. Several production helicopters probably qualify as test beds for the program. A program schedule is shown in Figure 6-4.

Provided the recommended program could be coupled with an existing digital fuel control development program and provided a NASA helicopter could be used in the flight phase, the contracted cost of such a program should not exceed $200,000.

6.3 FUTURE PROGRAMS FOR RCT RESEARCH

The studies of civil missions show that much of the pilot's manual workload can be improved by advanced control technology and improved displays.

The controllers of a conventional nature may be improved by incorporating force controllers to provide greater accuracy and by use of multiple-axis controllers.

Beyond this, however, the future of controllers should be associated with emphasis on the utilization of the pilot as the manager, and not as the controller of the aircraft. Table 6-1 outlines the types of control management that should be considered.

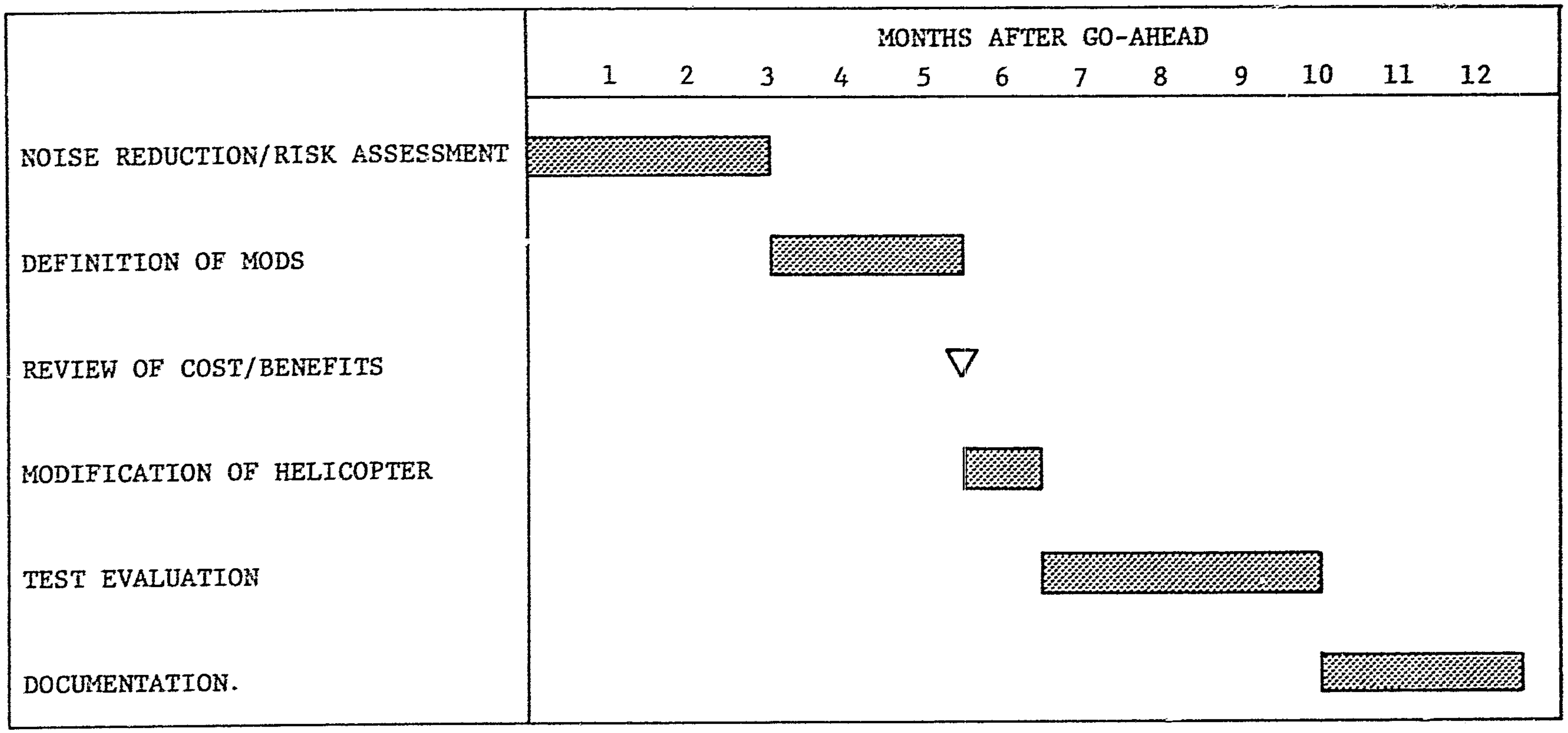

Figure 6-4. Rotorcraft noise-reduction program schedule.

TABLE 6-1. TYPES OF CONTROLS FOR RESEARCH (MANUAL & MANAGEMENT)

Type of Control	Configuration of Controller	Control Activation	Number of Axes Controlled
Manual Control	Hand/arm	Position	1 or 2
	Hand (side arm)	Force	1, 2, or 3
Control Management			
Override of auto control	Hand (side arm)	Force	1, 2, or 3
	Fingertip	Force or position	1, 2, or 3
Manuever select	Push-button	Push	-
Individual flight parameter select	Push-button plus fingertip controller	Push + force or position	1, 2, or 3
Flight vector select/ direct	Light pen or arrow or index on a sphere	Position set	1 vector
Voice	Speech	Speech	Could be in terms of desired position in earth axes or flight maneuvers or flight direction with rates or turn or climb, etc.

It includes modes where the pilot-manager may select certain maneuvers or flight parameters either to be controlled by himself or to allocate to an automatic control function, depending on his workload. The list progresses from partial autocontrol to full autopilot-directed in terms of the pilot's concept of flight vector rather than in terms of control of action about the axes of the aircraft. As one reads down the list, the ability of the system to unburden the pilot increases:

a. Pilot selects small maneuver segments to allocate to a control management system. This would be for short term maneuvers such as 1-minute hover, maximum power J climb, and maximum turn.

b. Pilot turns over individual flight parameter control to a control management system. As an example, the pilot could give control of heading, altitude, or even angle-of-attack to an automatic function.

c. Pilot programs full flight segments on auto pilot in terms of three-dimensional space and earth coordinates.

d. Pilot selects a flight vector to direct control management system.

In considering the unburdening of the pilot by the redesign of the controller, let us examine the steps through which the pilot must pass, both intellectually and by manual maneuvering, when he activates his controller:

a. He plans where he wants to be with respect to where he is now in some form of earth coordinates: X and Y positions.

b. He then adds altitude (Z) to his path from X to Y.

c. He converts the X-Y-Z positions along his desired flight path to rates (groundspeeds, airspeeds, rate-of-climb) and assigns times of departure and arrival.

d. He converts the rates and positions to aircraft performance, i.e., to maneuver in all six degrees of freedom as well as around the vertical, longitudinal, and lateral axes of his own aircraft, such as pitch or roll altitudes necessary to achieve the desired rate-of-climb or speed with associated power.

e. He then converts these desired aircraft positions to the required controller inputs needed to achieve them.

This is in terms of movement of the cyclic stick, the collective pitch control, the foot pedals, and the throttle. We may improve the pilot's planning time, and even his accuracy, if we can require him to go through fewer conversions of the X-Y-Z data. Toward this end, a series of control management systems in Table 6-1 is suggested.

If, in the future, we can then reduce the number of these steps, we can simplify the pilot's tasks and the time required for him to traverse through them prior to activating his controller.

7. CONCLUDING REMARKS

This study of active control technology and related cockpit technology and the assessment of the benefits of these technologies for future civil rotorcraft has resulted in both a qualitative and quantitative comparison of the gains to be achieved through continued development and fielding of the defined capabilities. The technology review confirms the study conclusion that active control technology is ready for full engineering development. More specifically, this study has identified a multicyclic rotor control system which achieves the following:

- Significant reductions in vibrations through reduction of hub shears and moments (e.g. up 91 percent reduction in 4/rev hub shears.)
- Control system weight reduction of 9 percent.
- Reduction of rotating control/rotor hub drag by 40 percent.
- A fixed cost, which is approximately 64 percent higher than a conventional control system; however, it is a system providing inherent advantages as noted above.

The investigation of the related cockpit technology assessed a number of civil missions and identified the cargo and construction mission as one of the more representative and difficult to perform. Using this mission as a basis, various cockpit concepts were examined with findings as follows:

- The highest workloads (both displays and controls) occurred during load hookup and release.
- Improvements in the active control technology (ACT) resulted in directly related cockpit technology (RCT) improvements.
- The defined cockpit concept reduces pilot workload for critical mission segments, e.g. as much as 178 percent for visual tasks and 25 percent for manual.

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Appendix A

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Appendix B

ACT/RCT BASELINE CASES

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ACT/RCT BASELINE CASES

Gross Weight (lb)	CG Station (in)	Airspeed (kn)	4/Rev cos	X Shear sin	4/Rev cos	Y Shear sin	4/Rev cos	Z Shear sin
11,600	144	80	-13.733	11.710	13.528	5.926	-106.110	34.632
11,600	144	110	-30.375	44.358	38.595	13.786	-110.387	136.179
11,600	144	140	-77.841	99.950	91.862	58.039	-159.151	373.695
11,600	130	80	-37.437	29.702	34.122	31.834	-51.536	-2.715
11,600	130	110	-71.825	81.557	73.234	58.419	-9.888	82.228
11,600	130	140	-146.494	157.256	134.566	134.641	58.623	305.338
7,500	144	80	-4.357	21.260	20.281	-3.215	-38.804	62.687
7,500	144	110	-12.066	54.670	47.908	-2.120	-77.637	155.217
7,500	144	140	-21.548	123.545	120.205	-1.658	-137.092	254.928
7,500	130	80	-12.559	32.267	31.368	7.159	-33.891	32.864
7,500	130	110	-34.939	78.012	72.081	22.112	-42.768	90.537
7,500	130	140	-60.319	159.969	153.107	41.333	-28.191	173.761