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THE STATE OF THE ART OF GENERAL AVIATION AUTOPILOTS

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SUMMARY

This report presents the results of a study performed under NASA Contract NAS1-16255, General Aviation Autopilot Study. The work was performed at the University of Kansas Center for Research, Inc., Flight Research Laboratory, by the authors under the guidance of Dr. Jan Roskam, Ackers Distinguished Professor of Aerospace Engineering. The study was conducted to provide the NASA-Langley Research Center with fundamental, background information about the state of the art of general aviation autopilots. The study is based on the information obtained from a general literature search, product literature, and visitations and interviews with manufacturers, users, and service centers. State-of-the-art autopilots are documented with respect to total systems, components, and functions. Recommendations concerning potential areas of further research are also presented.

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LIST OF ACRONYMS

Acronym	Definition
ADI	attitude director indicator
AFCS	automatic flight control system
ARC	Aircraft Radio and Control, Inc.
AS	Aeronautical Standard
B/C	back course
CRT	cathode ray tube
CWS	control wheel steering
DG	directional gyro
DME	distance measuring equipment
EADI	electronic attitude director indicator
EHSI	electronic horizontal situation indicator
EMDO	Engineering and Management District Office
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FD	Flight Director
GA	General Aviation
GS	glide slope
HSI	horizontal situation indicator
HUD	head up display
IAS	indicated airspeed
IFCS	integrated flight control system
ILS	instrument landing system
LaRC	Langley Research Center
LED	light emitting diode

LIST OF ACRONYMS (continued)

Acronym	Definition
LOC	localizer
MTBF	mean time between failure
MTBR	mean time between removal
N/A	not available or not applicable
NASA	National Aeronautics and Space Administration
PNI	pictorial navigation indicator
R & D	research and development
RNAV	radio navigation
SOA	state of the art
STC	supplemental type certificate
TC	type certificate
TSO	technical standard order
VG	vertical gyro
VOR	VHF omnidirectional ranging

CHAPTER 1

INTRODUCTION

This report documents a study performed under NASA contract NAS1-16255, titled: General Aviation Autopilot Study. The study was conducted for the purpose of providing the NASA-Langley Research Center with fundamental, background information about three aspects of general aviation (GA) autopilots:

1. The state of the art (SOA) of autopilot technology
2. The autopilot industry
3. Possible areas of improvement

This information will be used to determine where further research should be directed and, generally, to assist NASA/LaRC in planning its overall GA program.

1.1. METHODOLOGY

The research work required in this study was executed in three phases:

1. General literature search
2. Collection of product literature (including cost data)
3. Visitations and interviews with manufacturers, users, and service centers

All phases proceeded more or less simultaneously so that information obtained in any one phase could be followed up or investigated using the sources associated with the other two phases. Each phase is discussed in some detail in the following.

1.1.1 Literature Search

As specified in the contract, it was necessary to compile a bibliography of autopilot research. In addition, it was of interest to study all pertinent literature on the subject of GA autopilots. Initially, two methods were used to obtain this information: a computer literature search and a survey of reference indices available at the University of Kansas libraries. As a follow-up, references listed in articles found by the above methods were also surveyed. Articles that were informative were either copied and filed for future study or, if they were not available from the library and the titles implied great importance, ordered from the publishing agency. Papers with titles that implied questionable value were merely documented in the event they were needed in the future.

The first search was conducted using a computerized information retrieval service. The computer scanned reference indices for titles which contained certain key words. The key words applied to this search were:

1. Autopilot
2. Automatic pilot
3. Automatic flight control
4. Stability augmentation

The titles which contained these words were then cross referenced with the words:

1. General aviation
2. Light aircraft

The sources scanned were the Institute of Electrical Engineers, the National

Technical Information Service, and the Engineering Index.

There were five reference indices surveyed in the K.U. Libraries:

1. Applied Science and Technology Index
2. Engineering Index
3. Reader's Guide
4. Scientific and Technical Aerospace Reports
5. International Aerospace Reports

The main headings of interest were:

1. Autopilots
2. Aeronautic instruments
3. Avionics
4. Air navigation
5. Airplanes (light)
6. Airplane stability

The bibliography resulting from this search can be found in Chapter 6, Section 6.2. All other references used are listed in Section 6.1.

1.1.2. Product Literature Procurement

Product literature is defined here as any sales information which describes the modes, features, and any other characteristics of marketed autopilots that would be of interest to a prospective buyer. This includes purchase cost information given for both the total system and component levels.

Before making any requests for product literature, a list of GA autopilot manufacturers was prepared using the listing given in Reference 1 as a baseline. Other manufacturers were added as they were discovered.

The sales or marketing divisions of all manufacturers on the final list (Chapter 2) were contacted by telephone. Each manufacturer was asked for all available product literature associated with each autopilot being marketed. Product literature was received from each company which was contacted.

1.1.3. Visitations

The final source used to garner information about GA autopilots was personal interviews with individuals working in various areas of the autopilot industry. In addition to receiving verbal information, these visitations often yielded additional printed matter, such as autopilot maintenance manuals, failure data, pilot operating manuals, and certification procedures.

The organizations visited are described in Table 1.1. All commercial identifications have been replaced with single letter identifiers in accordance with NASA policy and out of fairness to those organizations which were not visited. A summary of the notes taken during each visitation is presented in Chapter 5. Organization H represents a group of various service engineers and technicians which attended a training school given by an autopilot manufacturer.

1.2. APPROACH AND SCOPE

During the course of this study, it became obvious that the general aviation autopilot industry is well developed. Many GA autopilots, by virtue of several recent developments, have more capabilities and greater reliability than most of their counterparts in the commercial transport

TABLE 1.1. SUMMARY OF VISITATIONS

Organization	Type	Position of person(s) interviewed	Subjects discussed
A	Autopilot manufacturer	Chief, special programs	design, operation, research
B	Autopilot manufacturer	Chief engineer, flight controls	design, operation, failures, research
C	Autopilot manufacturer	Engineer, flight controls	failures, research, future trends
D	Autopilot manufacturer	Engineer, flight controls	capabilities, research, trends
E	Airframe manufacturer	Systems engineers flight test engineers	flight test, certification, deficiencies
F	Airframe manufacturer	Avionics engineer	deficiencies, future trends
G	Aircraft delivery service	Pilot	deficiencies, suggestions
H	Service center	Service technicians, engineers	failures, deficiencies, suggestions
I	FAA Engineering and Management District Office (EMDO)	Systems certification engineer	certification, procedures, requirements

industry*

Also, a wide variety of autopilots is available to the GA aircraft owner since standardization is virtually nonexistent and so many different companies manufacture autopilots. As a result, autopilots which have more or less the same capabilities often use different methods and approaches to achieve them. It is for this reason that only the most common types of devices and subsystems will be discussed in detail.

This report can be looked upon as a basic guide to state-of-the-art, GA autopilots, from simple wing levelers to fully integrated flight control systems. The operation and capabilities of GA autopilots is described to permit a comparison with commercial and military autopilots. The industry and technology is assessed and possible areas of improvement are identified.

Autopilot operation is explained in Chapter 3. This chapter is nontechnical in nature. It explains the basic theory of operation of GA autopilots from three points of view: complete autopilot systems, individual autopilot components, and autopilot modes and features. Cost data are given for both the total system and component levels, along with performance information where it was available.

Chapter 4 briefly outlines certification practices and procedures, and gives the sources of information which define certification requirements in detail.

Chapter 5 summarizes the comments and suggestions made by industry personnel during interviews. These form the basis for the concluding remarks and recommendations of further research also included in that chapter.

Chapter 6 comprises a bibliography of recent and current research being

*except for structural mode control and automatic take-off and landing capability.

conducted in the field of GA autopilots.

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CHAPTER 2

GENERAL AVIATION AUTOPILOT MANUFACTURERS

Table 2.1 presents an alphabetical listing of major U.S. general aviation autopilot manufacturers. Some remarks concerning the primary type of GA market serviced is also given for each manufactuer. It should be noted that this list is by no means complete. Several companies which presently hold a relatively small share of the autopilot market or which manufacture certain autopilot components (without marketing complete systems) are not listed.

TABLE 2.1. GENERAL AVIATION AUTOPILOT MANUFACTURERS

MANUFACTURER	REMARKS
Aircraft Radio and Control Division Cessna Aircraft Rockaway Valley Road Boonton, NJ 07005 201-334-1800	light singles through heavy twins
Astronautics Corp. of America 2416 Amsler Street Torrance, CA 90505 213-326-8921	light, heavy singles; some light twins
Bendix Avionics Division 2100 N.W. 62nd Street P. O. Box 9414 Fort Lauderdale, FL 33310 305-776-4100	heavy singles through heavy twins
Brittain Industries, Inc. Hangar 12, Tulsa International Airport Tulsa, OK 74151 918-836-7701	light singles through light twins
Collins Divisions, Rockwell International 400 Collins Road, N.E. Cedar Rapids, IA 52406 319-395-1000	heavy twins, business jets
Edo-Aire Mitchell P. O. Box 610 Mineral Wells, TX 76067 817-325-2517	light singles through heavy twins
Jet Electronics and Technology, Inc. 5353 52nd S.E. Grand Rapids, MI 49508 616-949-6600	exclusively Learjet models
King Radio Corporation 400 N. Rogers Road Olathe, KS 66061 913-782-0400	heavy singles through business jets
Sperry Flight Systems, Avionics Division P. O. Box 29000 Phoenix, AZ 85038 602-866-0400	primarily business jets

CHAPTER 3

STATE OF THE ART OF GENERAL AVIATION AUTOPILOT TECHNOLOGY

3.1 INTRODUCTION

This chapter presents a general description of the state of the art of GA autopilot systems and their components. The term "autopilot" is defined here as any aircraft subsystem designed to control automatically the motions of the aircraft. The functions of an autopilot can include, but are not restricted to, all or a combination of any of the following functions:

1. Pilot fatigue relief
2. Maneuvering control
3. Automatic navigation
4. Automatic tracking
5. Automatic takeoff and landing
6. Structural mode control
7. Gust alleviation
8. Stability augmentation

However, GA autopilots as a class have not yet achieved the level of sophistication required to employ automatic takeoff and landing, structural mode control, or gust alleviation. This does not mean that GA autopilots can be considered unsophisticated. The advent of digital technology, microprocessing, and integrated circuitry have helped autopilot technology to improve rapidly in recent years, as will be shown.

The term "autopilot" is being used here to generalize three types of autopilot:

1. Wing leveler

2. Automatic flight control system (AFCS)

3. Integrated flight control system (IFCS)

Certainly, all three can be called automatic flight control systems, but the term is used here to imply capabilities more numerous than those of relatively simple wing levelers, yet not so numerous and advanced as integrated flight control systems. This classification is strictly arbitrary; there are no distinct dividing lines between categories 1, 2 and 3.

All airplanes falling within the range of light, single-engine airplanes to executive business jets are classified as "general aviation." The general rule is that the more complex and sophisticated airplanes utilize the more complex and sophisticated autopilots.

Section 3.2 describes the state of the art of complete GA autopilot systems in general, while Section 3.3 addresses autopilot components individually. Section 3.4 describes the modes and features which are currently available on GA autopilots.

3.2 AUTOPILOT SYSTEMS

As stated before, autopilot systems can be roughly divided into three categories. These are defined as follows:

1. Wing leveler: incorporates basic attitude, heading hold; possibly limited navigation capabilities.
2. Automatic flight control system: in addition to wing leveler, full navigation control including glideslope; also can have such features as go-around, back course, control wheel steering and altitude preselect.
3. Integrated flight control system: in addition to AFCS, offers

flight director and often air data computer.

Again, this classification system is arbitrary.

A listing of most of the currently available autopilots is presented in Table 3.1. This listing shows the major available and optional modes and features offered with each autopilot, in addition to an approximate list purchase price. Some prices are not given either because they were not available, or because the autopilot is not offered as an "off-the-shelf" item. The latter occurs if the model has been sold in volume as standard equipment on a fleet of airplanes. A unit list price in such a case is not available.

3.2.1 Functional Description

A block diagram of a typical autopilot is presented in Figure 3.1. The system is activated by the human pilot who engages the desired function (attitude hold, VOR capture, go-around, etc.) via the autopilot (= system) controller. This command enables the autopilot computer to receive signals from the appropriate sensor(s). The computer processes these signals and computes the proper commands to be sent to the applicable actuators. The actuators in turn act upon the primary flight control system to produce a proportional control surface deflection, which results in the necessary aircraft motion. This motion is detected by the sensor(s) and fed back to the autopilot computer and the pilot (via cockpit displays). It is important to note that the only components that are always unique to the autopilot are the computer, the actuators, and the controller. Often the sensors and the displays are standard equipment and are interfaced with the autopilot when it is installed. Other associated components are the power source and the media through which the signals are transmitted. Each of these components is discussed in Section 3.3.

TABLE 3.1. SUMMARY OF GENERAL AVIATION AUTOPILOTS

MANUFACTURER	MODEL	NO. OF AXES	WING LEVELER	PITCH ATTITUDE HOLD	HEADING HOLD	HEADING PRESELECT	VOR/LOC TRACK	VOR/LOC CAPTURE	GLIDE SLOPE TRACK	GLIDE SLOPE CAPTURE	ALTITUDE HOLD	ALTITUDE PRESELECT	IAS HOLD	MACH HOLD	VERT. SPEED HOLD	BACK COURSE	GO AROUND	TURN COMMAND	PITCH COMMAND	AUTO TURN COORDINATION	PITCH SYNCHRONIZATION	AUTO TRIM	YAW DAMPER	FLIGHT DIRECTOR	BASIC SYSTEM COST ($)
ARC	200A	1	●		●		●	●								●									1620
	300A	1	●		●	●	●	●								●									3340
	400	2	●	●	●	●	●	●										●	●						5910
	400A	2	●	●	●	●	●	●	●	●	●					(○)	(○)	●	●		●	●		(○)	9600 (3 IN. FD-16,195)
	400B	2	●	●	●	●	●	●	●	●	●					(○)	(○)	●	●		●	●	○	○	9600 (3 IN. FD-16,335)
	800B	3	●	●	●	●	●	●	●	●	●					●	●	●	●		●	●	●	●	23,235 (4 IN. FD)
	1000A	3	●	●	●	●	●	●	●	●	●	○				●	●	●	●		●	●	●	●	32,765
ASTRONAUTICS	P1	1	●		●																		○		1495
	P2	1	●		●	●	●																○		1695
	P2A	1	●		●	●	●	●															○		2995
	P3	2	●	●	●		●				●												○		5790
	P3A	2	●	●	●	●	●	●			●												○		6952
	P3B	2	●	●	●	●	●	●	●	●	●											●	○		7995
BENDIX	M4-D	3	●	●	●	●	●	●	●	●	●					●	●	●	●		●	●	●	●	35,414*
	FCS-810	2	●	●	●	●	●	●	●	●	●					●	●		●		●	●		●	17,682
	FCS-870	3	●	●	●	●	●	●	●	●	●		○			●	●		●	○	●	●	○	●	11,716
BRITTAIN	B-5, B-7	3	●	●	●	●	●	●			●		●					●		●					NOT AVAILABLE
	IAV-FLITE II	2	●		●	●	●	●												●					NOT AVAILABLE
COLLINS	APS-80	3	●	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●	●	●		○	○	22,717
	AP-105	3	●	●	●	●	●	●	●	●	●		●	●	●	●	●	●	●	●	●		○	○	19,133
	AP-106A	3	●	●	●	●	●	●	●	●	●		●	●		●	●	●	●	●			●	●	17,498
EDO-AIRE MITCHELL	CENTURY I	1	●		○		○																○		1920
	CENTURY II	2	●		○		○																○		2894
	CENTURY III	3	●	●	●		○				●											●	○		6742
	CENTURY IV	3	●	●	●	●	●	●	●	●	●					(○)	●					●	○	(○)	9675 (11,585)
	CENTURY 21	2	●	●	●	●	●	●								●					○				3950
	CENTURY 41	3	●	●	●	●	●	●	●	●	●					●	●				●	●	○		9785
	CENTURY 41	3	●	●	●	●	●	●	●	●	●					●	●		●		●	●	○	●	14,669
JET	FC-110	3	●	●	●	●	●	●	●	●	●					●		●	●		●	●	●		NOT AVAILABLE
	FC-200	3	●	●	●	●	●	●	●	●	●		●	●	●	●	●	●	●		●	●	●		NOT AVAILABLE
KING	KFC 200	2	●	●	●	●	●	●	●	●	●					●	●		●		●	●		●	10,715
	KFC 200	3	●	●	●	●	●	●	●	●	●					●	●		●		●	●	●	●	12,390
	KFC 250	3	●	●	●	●	●	●	●	●	●	●				●	●		●		●	●	●	●	28,973**
	KFC 300	3	●	●	●	●	●	●	●	●	●	●	●			●	●	●	●	●	●	●	●	●	43,688**
	KAP 200	2	●	●	●	●	●	●	●	●	●					●					●				10,165
	KAP 200	3	●	●	●	●	●	●	●	●	●					●					●				11,940
SPERRY	SPZ-200A	3	●	●	●	●	●	●	●	●	●	●	●		●	●		●	●	●	●		●	●	NOT AVAILABLE
	SPZ-500	3	●	●	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●	●	●	●	●	NOT AVAILABLE
	SPZ-600	3	●	●	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●	●		●	●	NOT AVAILABLE
	SPZ-700***	3	●	●	●	●	●	●	●	●	●	●	●		●	●		●	●	●	●		●	●	NOT AVAILABLE

● -STANDARD
○ -OPTIONAL

FD-FLIGHT DIRECTOR

*LACKS REMOTE VERTICAL GYRO
**WITH JET VERTICAL GYRO
***WITH MICROWAVE LANDING SYSTEM

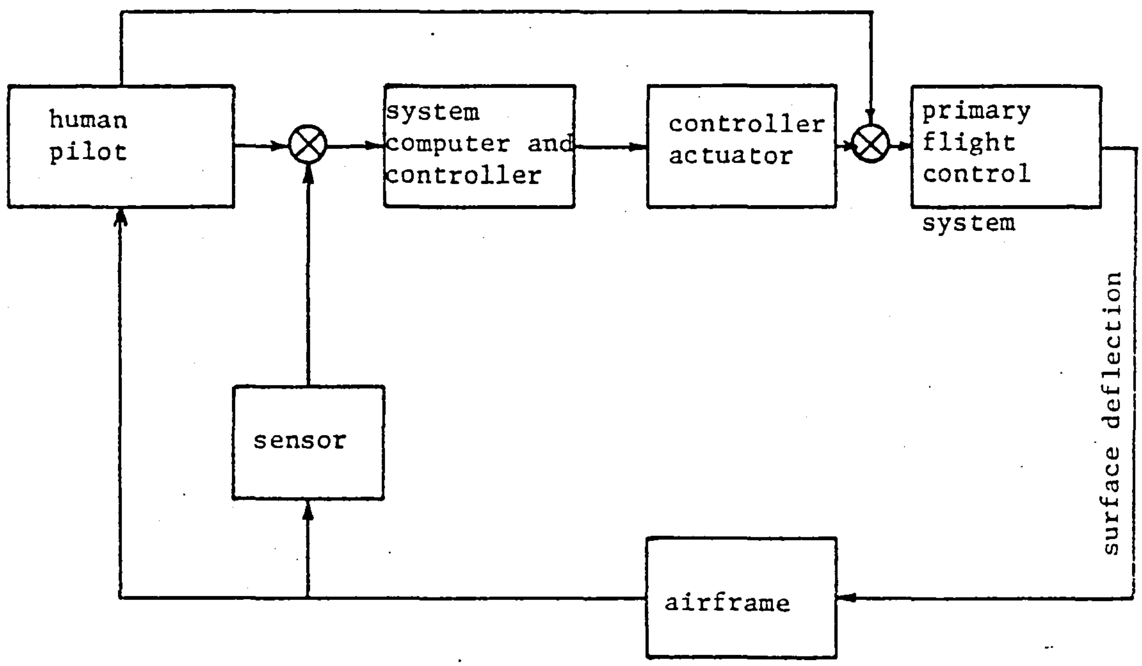


Figure 3.1. - Typical autopilot block diagram (Reference 2).

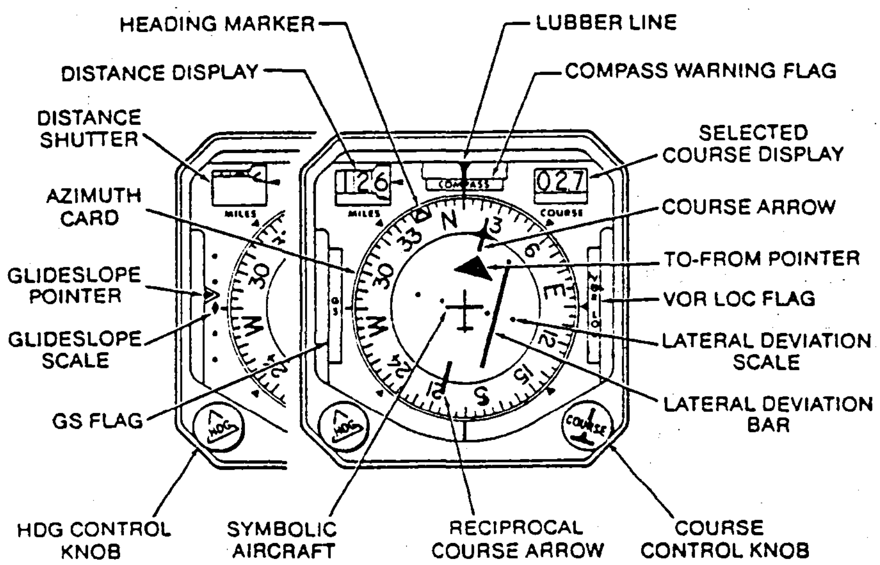


Figure 3.2. - Typical horizontal situation indicator (Reference 3).

3.2.2 Cost

As mentioned earlier, the list price of each major autopilot model currently marketed is given in Table 3.1. These values are often estimates because many autopilots offer a variety of versions of the same component, one of which had to be arbitrarily chosen in compiling the data. The wide range of prices is indicative of the wide range of capabilities available.

Installation cost data or estimates were not available from any of the manufacturers or installers that were contacted because the cost of installing an autopilot can vary widely from airplane to airplane. One manufacturer obtains a "ball-park" figure for installation cost by assuming that it is roughly equal to purchase cost.

Purchase cost data for individual components are presented in Section 3.3.

3.2.3 Reliability and Failure

Reliability and failure rate data were generally not available from manufacturers or operators because either records were not kept or the information was considered to be proprietary. Most manufacturers cited Military Specification MIL-217b as being a good reference guide for estimating the mean time between failure (MTBF) for a given system or component. However, most autopilot manufacturers use their own in-house methods, which are carefully tailored to predict the reliability of their designs.

One airframe manufacturer did supply mean-time-between-removal (MTBR) data for one IFCS offered as original equipment on one of their twin turboprop models. The autopilot manufacturer in that case predicted a total system MTBR of 180 hours, which is low for autopilots of its class. Predicted MTBR data are provided for some individual components of this autopilot in Section 3.3. These data are considered to be somewhat representative of autopilot components of their class.

Component failure statistics were provided by the Federal Aviation Administration (FAA). These statistics are summarized in Table 3.2. The survey is based on the 597 autopilot failures reported to the Flight Standards National Field Office Maintenance Analysis Center from June, 1974, through May, 1980. Of these, 446 were determined to have occurred on general aviation aircraft. Table 3.2 also gives the number of failures as a percent of the total for each component which exhibited a significant number of failures. The specific sources of these component failures are given as a percent of the number of failures associated with the component to which each source is related. For example, 11.2 percent of all failures were sensor related, while 16.1 percent of those failures were tumbling or precessing gyros. It should be noted that these data differ with the opinions of many industry people (see Chapter 5).

3.3 AUTOPILOT COMPONENTS

3.3.1 <u>Displays</u>

3.3.1.1 Functional Description

3.3.1.1.1 Current Displays.- The horizontal situation indicator (HSI) or pictorial navigation indicator (PNI) is the primary navigation display. It shows inertial or magnetic direction, selected heading, and deviation from a radio navigation beam (see Figure 3.2). If so equipped, glideslope (GS) and distance measuring equipment (DME) display is also shown. In addition, warning flags show when the gyro loses speed, the GS or VOR/LOC radio signal has insufficient

TABLE 3.2. SUMMARY OF GA AUTOPILOT FAILURES

REPORTED TO THE FAA, 1974-1980.

Total failures reported: 446

Component/Source	Percent of component failures	Percent of total failures
Sensors		11.2
Defective	32.1	
Gyro tumbles, drifts	16.1	
Other	51.8	
Actuators		33.2
Damaged cable	30.1	
Clutch	10.4	
Broken shear pin, shaft or gear	9.6	
Jamming or binding	9.3	
Solenoid failure	5.6	
Defective	3.3	
Other	31.7	
Electrical		35.0
Circuit component (transistor, capacitor, etc.)	35.7	
Switch	18.0	
Defective board	14.9	
Board failure	11.4	
Connector	9.7	
Other	10.3	
Other		14.1
Improper installation	38.3	
Out of adjustment	28.4	
Wear or corrosion	11.3	
Installation impossible	11.0	
Other	11.0	
Not Discernable		6.5

strength, or other failures that may render the display invalid. The display is generally mechanically linked to the directional gyro. One manufacturer has produced an HSI which has the gyro output interfaced directly with a digital microprocessor. The microprocessor commands a digital- or stepper-motor to drive the azimuth card to indicate the proper heading.

The artificial horizon shows existing aircraft pitch and roll attitude, calibrated in degrees. This instrument is often mechanically linked to its vertical gyro. More sophisticated artificial horizons are called attitude director indicators (ADI's). These ADI's are usually a part of an IFCS and can display things similar to those displayed by the HSI. The primary difference between an artificial horizon and an ADI is the flight director, which displays on the ADI the commands necessary to perform the desired autopilot function. There are two types of flight director:

1. Single cue, or V-bar
2. Double cue, or cross pointer.

The appearance and function of these are illustrated in Figures 3.3 and 3.4, respectively. With the flight director and autopilot engaged, the aircraft will follow the flight director bars. Thus, the flight director is a good indication of an autopilot failure, since the autopilot drives it. This is why many pilots engage the flight director before engaging the autopilot.

The mode annunciator shows which modes of the autopilot are engaged. Usually, either a light under each mode selector button is turned on when it is depressed or a separate panel is installed with the individual modes printed and illuminated on it.

3.3.1.1.2 Advanced Displays.- Most research in the advanced display area has been aimed at light emitting diodes (LED's) and cathode ray tubes (CRT's).

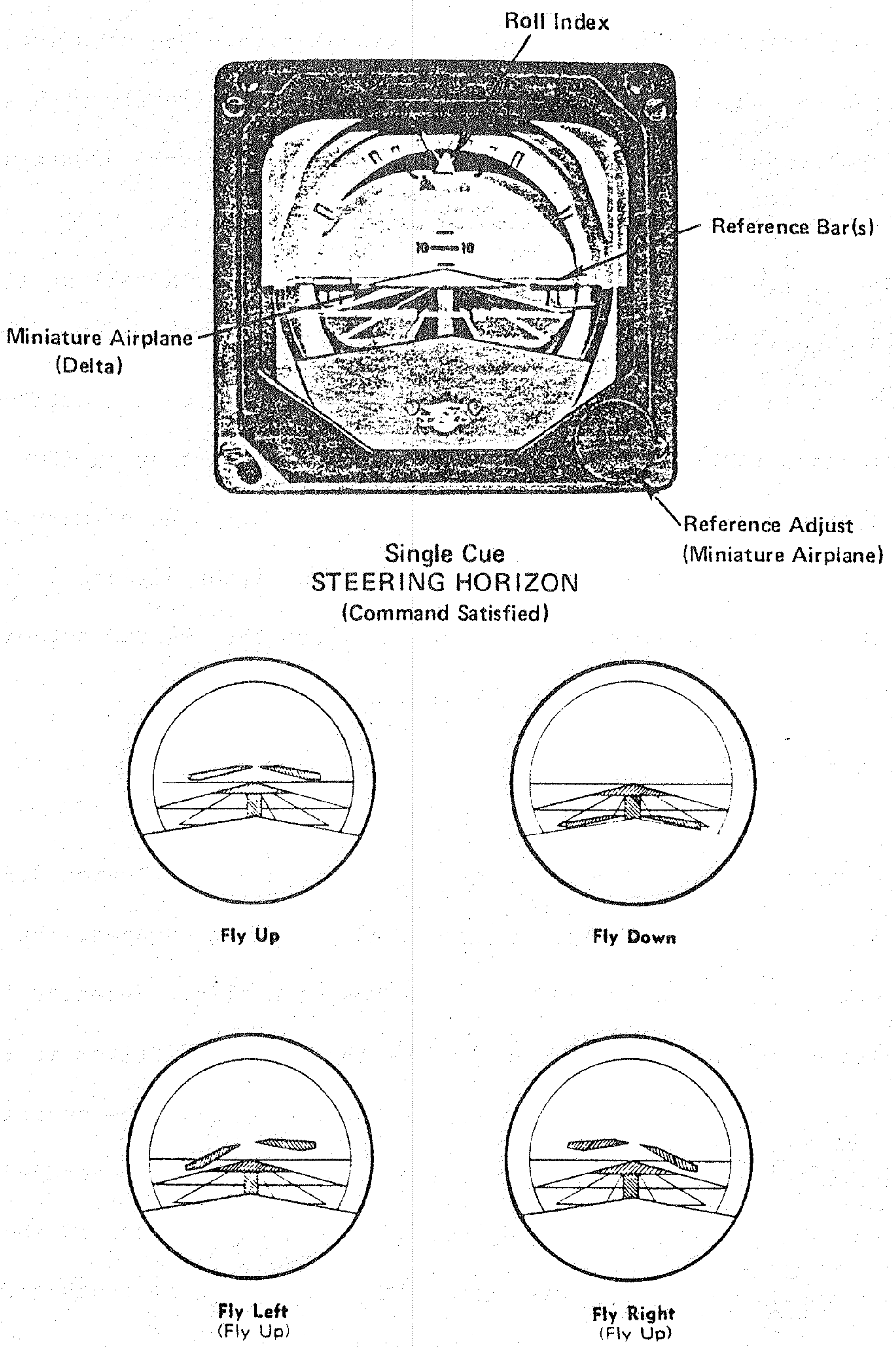


Figure 3.3. - Typical single cue attitude director indicator (Reference 4).

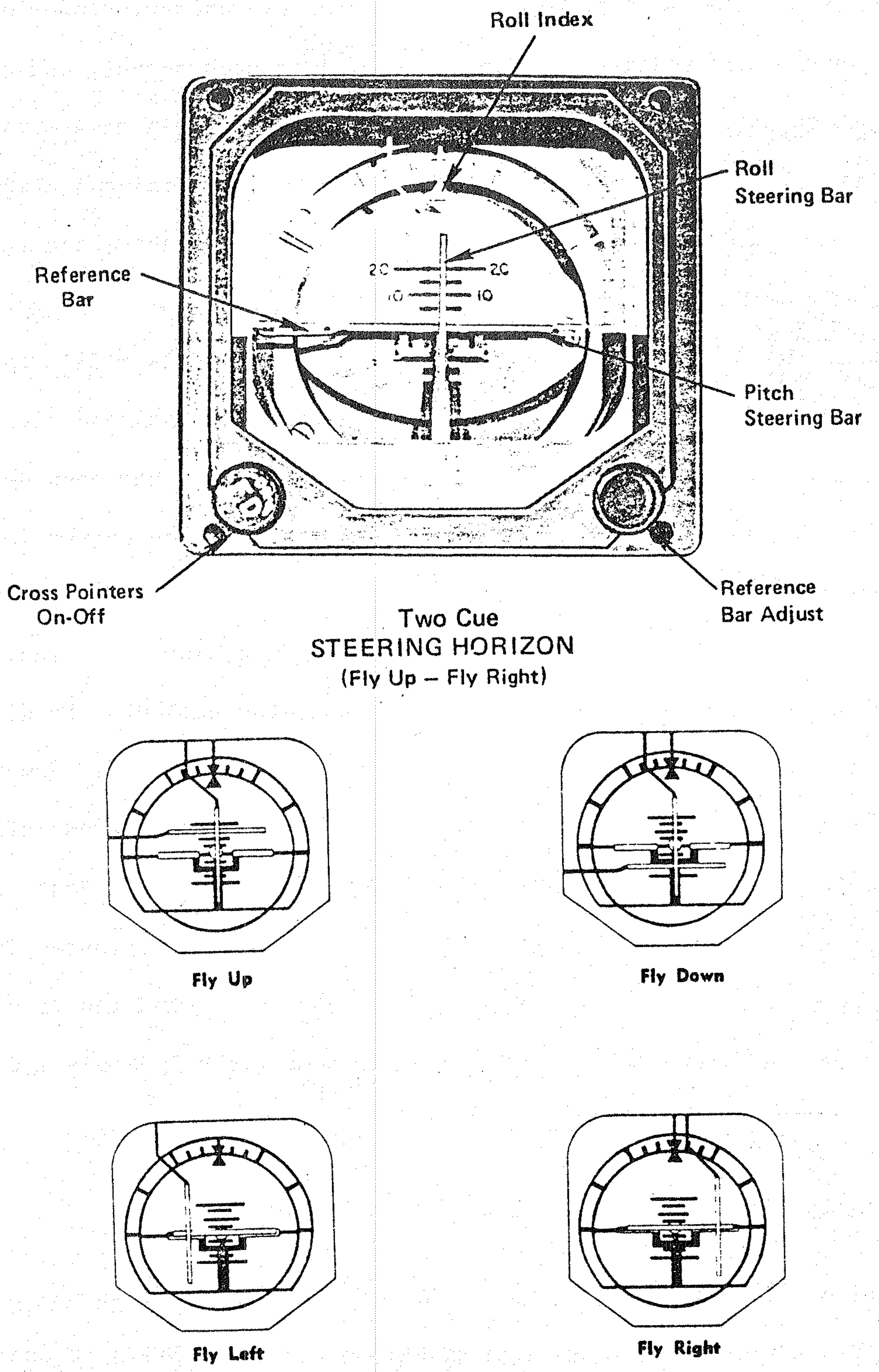


Figure 3.4. - Typical double cue attitude director indicator (Reference 4).

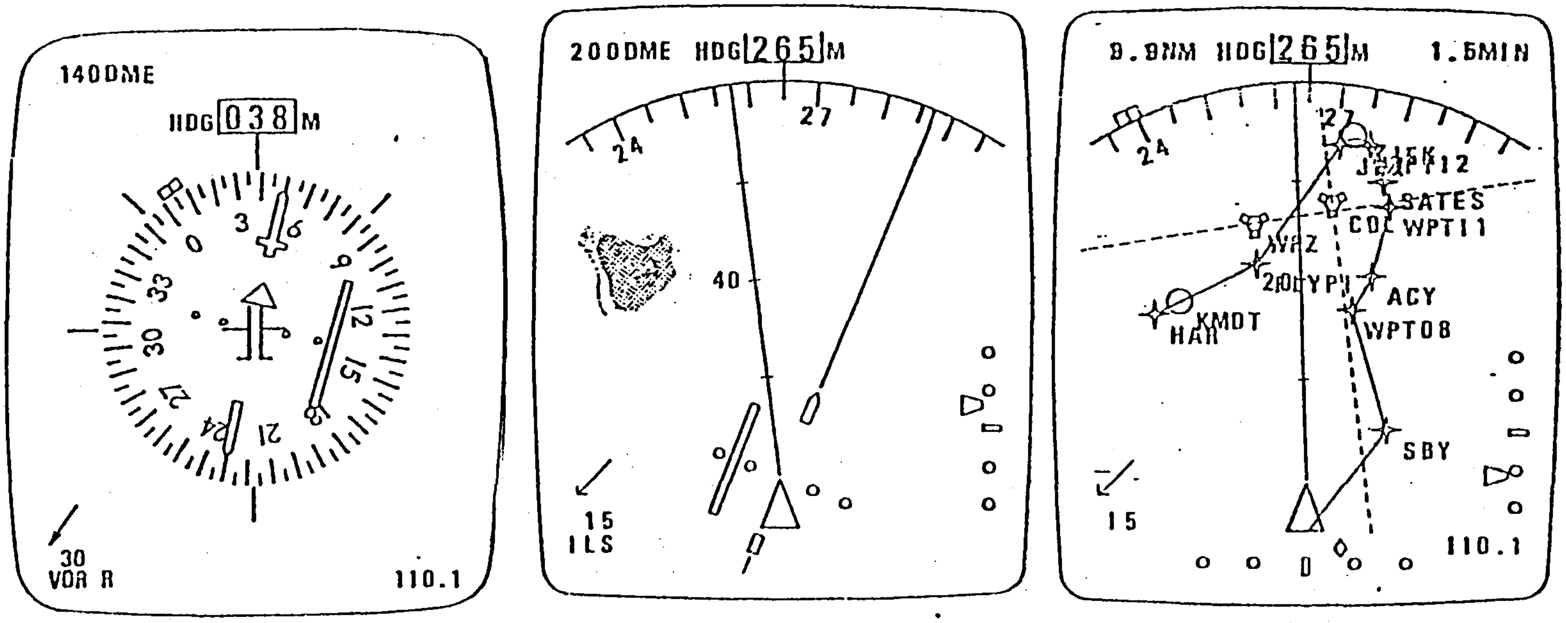
LED's appear to have the most promise in displaying alphanumeric information; VOR/LOC frequencies and radial selection, DME, IAS or Mach number, and altitude are examples. The use of LED's has already been instituted in many more advanced systems. CRT's are capable of displaying both pictorial and alphanumeric information. ADI and PNI functions as well as those listed above can be displayed. In addition, one display area can be used to show whichever particular display is desired. Figures 3.5 and 3.6 show the many formats a CRT can exhibit.

Research into flat panel displays such as the plasma panel and electroluminescent displays is well under way. In fact, a flat CRT has been developed but the cost so far seems to be prohibitive. The major reason conventional CRT's are cost competitive is the large commercial computer terminal market.

Head-up displays (HUD's) can be very effective in easing the transition from looking inside to outside the cockpit. This system projects the display onto a semitransparent panel between the pilot and the windscreen. Thus the pilot need not move his line of sight and re-focus to read displayed information. This is especially beneficial during ILS approach. A more cost effective application may be the micro-HUD, which uses a pair of eyeglasses instead of the semitransparent panel. Some research has been completed and is under way in this area (Reference 6). Table 3.3 gives some typical display characteristics.

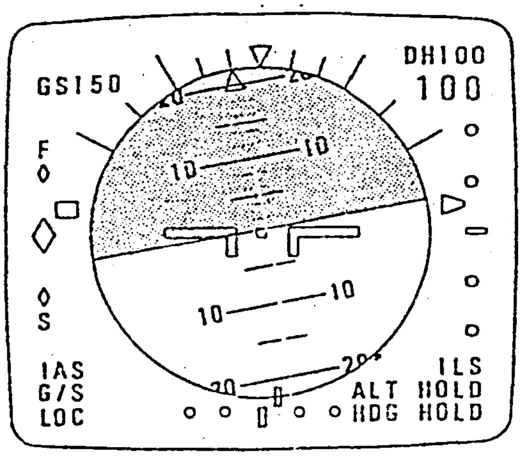
3.3.1.2 Installation

Information is generally displayed to the pilot from the instrument panel. However, limited space can be a problem in that area. This leads to one of two alternatives: reduced size of the sensor portion of a sensor-display unit or separation and remote installation of the sensor. The former is favored in



EHSI - VOR/ILS STANDARD HSI MODE EHSI MODIFIED VOR/ILS MODES EHSI MAP FORMAT

Figure 3.5. - Electronic horizontal situation indicator configurations (Reference 5).



EADI FORMAT

Figure 3.6. - Electronic attitude director indicator configuration (Reference 5).

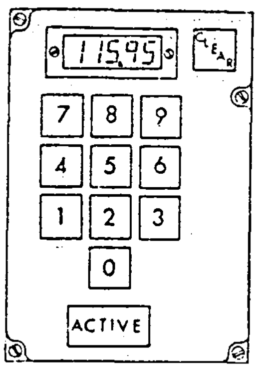


Figure 3.7. - Typical keyboard data entry device with LED display (Reference 7).

TABLE 3.3. TYPICAL DISPLAY CHARACTERISTICS

	Conventional				Advanced			
	Pictorial navigation indicator	Artificial horizon	Flight director	Mode annunciator	Cathode ray tube	Head up display	Flat display	LED's
Price range (dollars)	3500-5100	1000-1250	1800-3000 & up	150-270* 750-1500**	N/A	N/A	N/A	see paragraph 3.3.2.
Approximate weight, lbs (kg)	5.3-9.2 (2.4-4.20)	2.80-3.20 (1.27-1.40)	3.30-7.20 (1.50-3.30)	0.5*-2.9** (0.12-1.32)	N/A	N/A	N/A	
MTBF or MTBR (hrs)[a]	1500-3750	N/A	N/A	2000 (selector anncia-tion package)	7500 (predicted)	N/A	N/A	N/A
Input	analog or digital	analog	analog	analog	digital	digital	digital	digital
Output	mechanical pictorial	mechanical pictorial	mechanical pictorial	on/off	pictorial alpha-numeric	pictorial alpha-numeric	pictorial alpha-numeric	alpha-numeric
Remarks	3" slaved, with DG, VOR & CS meters	3" with VG	3" single cue with VG and FD computer	*annuciator only **annunciator /controller	Under R & D. Costs, failure rates, and weights are not well understood			

[a]Data from one manufacturer only

light aircraft because reduced size means reduced weight and cost. When greater accuracy is important, especially in the case of gyroscopes, increased size is often the solution. Unfortunately, remote installation incurs additional mounting and connection costs.

3.3.2 Data Entry Devices

Three types of data entry are usually required: 1) mode selection, 2) air data and 3) navigation.

The two primary methods for data entry are keyboards and conventional knobs. A typical keyboard data entry device is shown in Figure 3.7. Keyboards can be faster than knobs but, especially in turbulence, may be less accurate. In terms of space, if only a few pieces of data need to be entered, the conventional turn knobs are more efficient. For larger requirements, however, the keyboard will be the best choice, since one set can be used to input VOR/LOC, DME, RNAV, and communications frequencies into direct use or storage. Air data can be input also.

Mode control is usually achieved with push buttons. Each button is labeled with a mode and, when pushed, activates that mode. Pushing the button a second time or selecting an incompatible mode will deactivate the previous mode. Many autopilots automatically implement the track mode after a VOR/LOC beam has been captured.

Another type employs a rotary dial to select modes and must be turned manually from capture to track. See Figures 3.8 and 3.9 for examples of each type.

Until recently, navigation data entry has primarily been with knobs and mechanical dial readouts. Necessary data to be entered includes frequency,

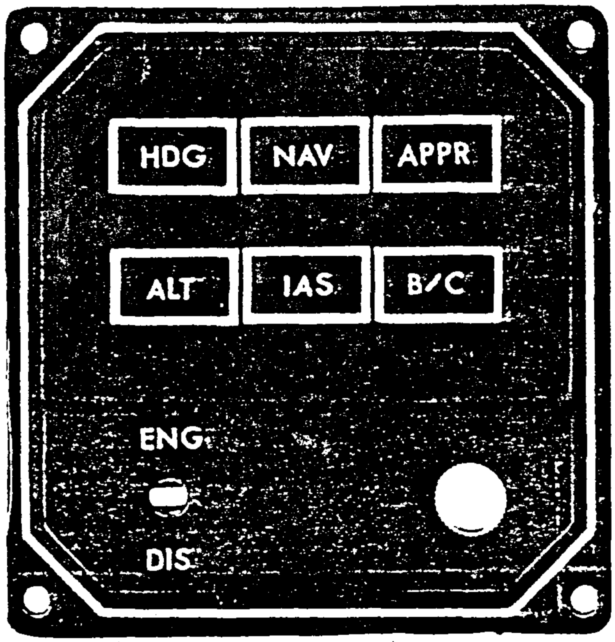


Figure 3.8. - Pushbutton mode controller/
annunciator (Reference 8).

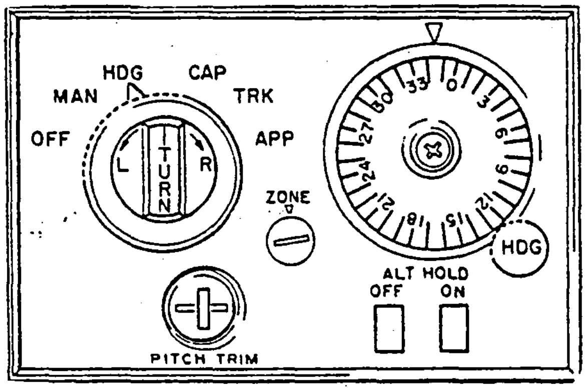


Figure 3.9. - Dial mode controller/annunciator
(Reference 9).

radial, and preselected heading. Each frequency selector is mounted directly on the appropriate receiver, and the heading bug is moved by a knob located on the HSI. Radial selection is on a separate indicator. Lately, movement has been toward the use of a keyboard and LED display for these functions (except for the heading bug) on more advanced systems. Example costs and weights for one manufacturer are shown in Table 3.4.

TABLE 3.4. TYPICAL DATA ENTRY DEVICE CHARACTERISTICS

Type	Display	Price	Weight
Keyboard	Frequency, Radial	$1540	1.04 kg
Knob	Frequency	$ 435	0.5 kg

Although area navigation (RNAV) computers cannot be considered autopilot components, they can be interfaced with autopilots, which is often the case with sophisticated aircraft. These devices require more data entry than any panel instrument. Since they are often linked to the autopilot, they should not be overlooked. Again, because of the variety of information that must be given to an RNAV computer, keyboard data entry is more efficient and is commonly incorporated. One brand of RNAV uses levers to select the desired radial and distance. The levers have click-stops that correspond to each of the nine digits in the mechanical-digital selector display. One lever is devoted to each digit in the desired frequency and distance. A rotary switch selects the desired waypoint.

Air data equipment usually requires only the preselected altitude as input. Knobs are conventionally used in this case.

Another company is investigating the feasibility of automatic data input with prerecorded magnetic cards. The cards could store any type of information but would be most useful for RNAV input. Conceivably, autopilot commands could be preprogrammed and input using this method. If required, changes in flight can be input manually.

3.3.3 Computers

Basic autopilots use a single device to manage and process signals from the sensors. In addition, amplifiers, switches, phase shifting networks, and dozens of other electrical components are required to make the proper conversion from sensor/input signals to actuator/output signals. In an autopilot, all of the above elements are combined into what will be referred to as a "computer." Some of the functions performed on the input signals are

1. Acceptance
2. Conversion (e.g., ac to dc)
3. Application of phase lead or lag
4. Amplification

Other peripheral devices which perform the first two functions and which can be interfaced with the autopilot computer are flight director and air data computers. In systems incorporating all three computers, the autopilot computer accepts processed sensor and command data from the air data and flight director computers, respectively. The autopilot computer then uses these data to decide which actuators need to be driven and how much voltage needs to be applied.

In the past, autopilot computers were all-analog in nature; but many analog/digital-hybrid computers have been introduced recently, and the trend toward all-digital systems is expected to continue in strength. Digital computers are not only competitive with their analog counterparts in cost, size, and weight but have the advantage of simplicity, speed, capacity, and capabilities that were not possible before (e.g., failure detection). In addition, interfacing a digital computer with other autopilot components is much simpler because these components (sensors, displays, actuators, etc.) are becoming digital themselves. Currently, analog-to-digital and digital-to-analog converters are required because all inputs and outputs are analog. Characteristics of typical one- and two-axis autopilot computers are given in Table 3.5.

TABLE 3.5. TYPICAL COMPUTER CHARACTERISTICS

Type	Price	Weight	MTBR*
One-axis	$1200	0.82 kg	N/A
Two-axis	$3800	1.05 kg	1000 Hrs

*One model only.

3.3.4 Sensors

The number of functions an autopilot can perform is reflected in the number of sensors that interface with the autopilot or with the air data computer. Generally, a separate sensor is required for each pertinent aircraft parameter; and a variety of methods of sensing or deriving each parameter are available to the autopilot designer. A listing of conventional sensors and their outputs is given in Table 3.6. It is beyond the scope of this study to discuss them all here; thus only the primary sensor types will be dealt with. The primary sensors are as follows:

1. Gyroscopes
2. Altitude sensors
3. Airspeed sensors

3.3.4.1 Current Sensors

TABLE 3.6. SENSOR APPLICATION (REFERENCE 2).

Sensor	Basic Output Quantity Longitudinal
Accelerometer and/or Airspeed detector	Forward velocity
Accelerometer and/or Local flow detector	Vertical velocity
Rate gyro	Pitching angular velocity
Accelerometer	Forward Acceleration
Accelerometer	Vertical Acceleration
Accelerometer and/or Local flow direction detector	Angle of attack
Stabilized gyro	Pitch angle
Angular accelerometer and/or two linear accelerometers	Pitching Acceleration
Altitude sensor	Altitude

Sensor	Basic Output Quantity Lateral
Accelerometer and/or Local flow direction detector	Side velocity
Rate gyro	Rolling angular velocity
Rate gyro	Yawing angular velocity
Accelerometer	Side acceleration
Stabilized gyro	Yaw angle
Angular accelerometer and/or two linear accelerometers	Yaw acceleration
Stabilized gyro and/or Rate gyro	Roll angle
Angular accelerometer and/or two linear accelerometers	Roll acceleration
Accelerometer and/or Local flow direction detector	Sideslip angle

3.3.4.1.1 Gyroscopes.- Gyroscopes (gyros) are used to sense airframe rates and angular displacements. The gyro is composed of a high speed rotor mounted in surrounding rings (gimbals). A typical arrangement is shown in Figure 3.10. Note that this gyro has two degrees of freedom. Since the rotor must conserve angular momentum, it remains fixed in inertial space if no torques are applied to it. Thus if the rotor is "free" (as in Figure 3.10), the aircraft may rotate about it in two axes (pitch and roll, here) without reorienting its axis of rotation in inertial space. The angular displacement of the aircraft can then be measured relative to the appropriate gimbal. If the rotor is restrained, the torque that must be applied to reorient its axis of rotation is proportional

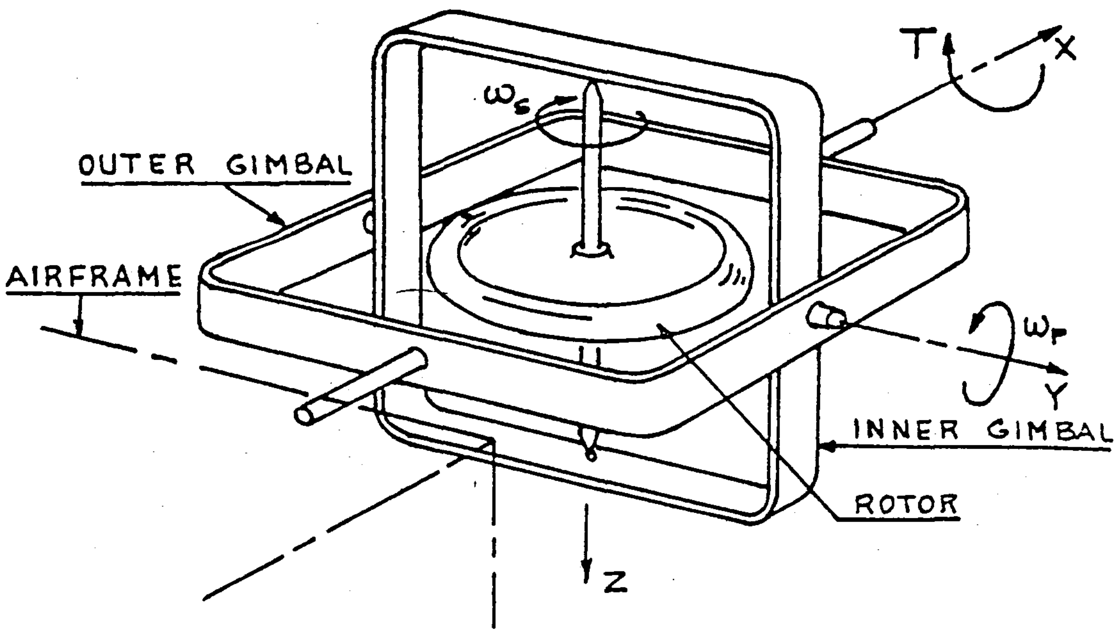


Figure 3.10. - Free gyroscope
(Reference 2).

to the rate of rotation of the aircraft. Thus the angular velocity of the aircraft can be determined by measuring the torque applied to the rotor. These concepts are discussed in detail in Reference 2.

A gyro used to sense the angular displacement of the aircraft is called a displacement gyro. The rotor can be driven electrically, but it is often driven pneumatically by drawing high-velocity air past a set of vanes fixed to the rotor. This produces a "paddle-wheel" effect which keeps the rotor spinning at high speed. A typical vacuum-driven rotor and housing are illustrated in Figure 3.11.

Displacement gyros can be mounted either immediately behind the indicator in the panel, or remotely. If panel mounted, the gyro directly drives the indicator mechanically, whereas remote mounting requires a device to sense the orientation of the gyro. This device signals a motor to drive the indicator. Although they are more expensive, remote gyros can conserve behind-the-panel space.

Whether panel or remote mounted, the gyro orientation must be sensed and converted to an electrical signal if the gyro is interfaced with an autopilot. By far, the two most common methods employed are an induction device (EI) and synchro pickoffs.

EI pickoffs derive their name from the shape of the two magnetic structures that compose them. Figure 3.12 illustrates the basic operation of an EI transformer. Each arm of the E is wound with a coil. The other coils generate the output, while the inner coil is connected to an a-c source. Either the E or the I can be fixed to the gimbal with the other mounted to the gyro housing, which in turn is mounted in the airframe. This transformer functions as an error detector when the reluctance between the inner coil and outer coils is

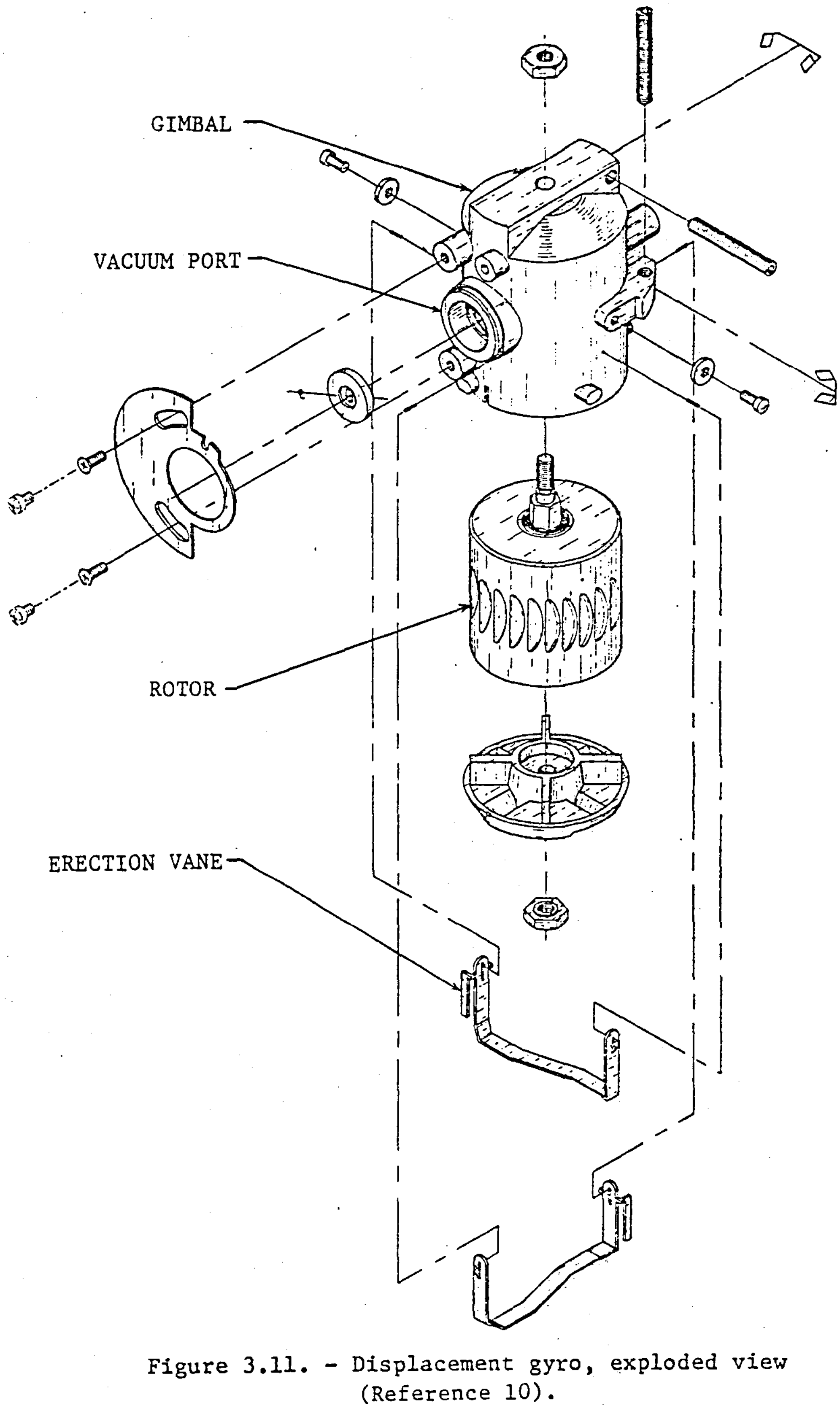


Figure 3.11. - Displacement gyro, exploded view
(Reference 10).

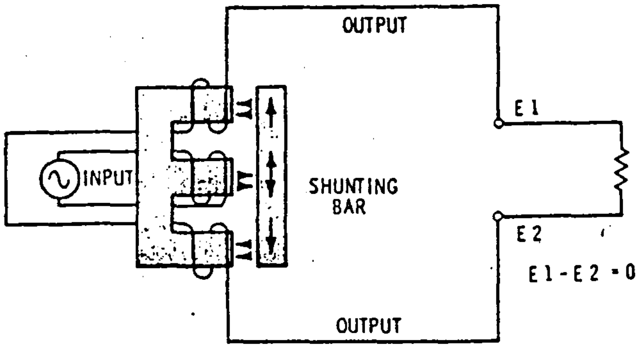


Figure 3.12. - EI transformer, general arrangement (Reference 11).

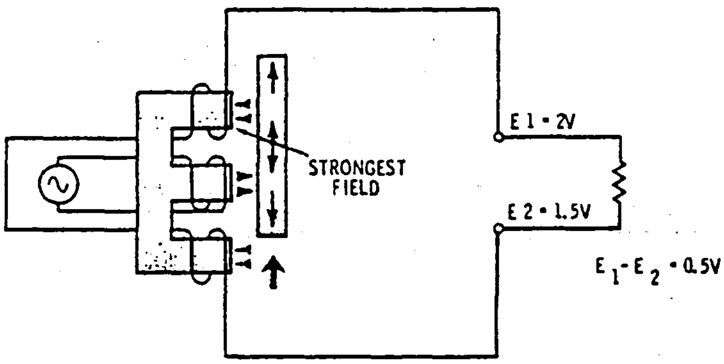


Figure 3.13. - EI transformer, error signal generation (Reference 11).

varied. When the shunting bar (I) is in the center position (which corresponds to the gyro reference), the reluctance between the inner coil and both output coils is equal. Thus the magnetic lines of force, and therefore the induced voltage in each coil, are equal. Since the output coils are wound such that the voltages induced into each coil are 180° out of phase, the error output voltage is zero. As the shunting bar is moved (a result of aircraft rotation), the reluctance between the coils varies. This is shown in Figure 3.13. More voltage is induced in the output coil with the least reluctance between it and the inner coil, and an error voltage is produced. This error voltage is proportional to the displacement of the shunting bar, which in in turn proportional to the aircraft angular displacement.

Synchro pickoffs function on the same principle as EI pickoffs. The difference is in the arrangement of the magnetic structures.

Pitch and roll attitude is sensed with a vertical gyro (VG); that is, a displacement gyro mounted with its spin axis oriented vertically, as in Figure 3.10. For proper orientation, the VG rotor can be aligned using one of two methods. The first method uses two pairs of opposing rotor exhaust-air erector jets, each mounted on pendulous erector vanes that act as air valves. If the rotor spin axis deviates from the vertical position, one jet opens more, and the other tends to close. The thrust from the open jet applies a torque to the rotor axle, realigning the rotor. Details can be found in Reference 9. The other method senses the vertical position with mercury switches or some other similar device. If the spin axis deviates from its vertical orientation, the switches close, activating a motor to realign the rotor.

Yaw attitude, or heading, is sensed with a directional gyro (DG). The DG-rotor spin axis is usually oriented so that it is parallel with the longitudinal centerline of the airplane. Realignment is most often done manually by resetting the compass card to agree with the magnetic compass indication. In flight, this must be done approximately every fifteen minutes. If the DG is equipped with magnetic slaving, manual alignment is not necessary. A magnetic slaving device senses the magnetic flux that results when the DG is not aligned with the earth's magnetic field. This flux creates a signal to a motor to realign the DG.

A gyro used to sense the rate of angular displacement of the aircraft is called a rate gyro. As stated earlier, a rate gyro is restrained and senses angular rate from the torque induced on its spin axis by the aircraft. Some rate gyros can sense rates in two axes. This is done by inclining (tilting) the spin axis in the appropriate direction and fixing it in this position. The gyro is then sensitive in the two axes that describe the plane of inclination. This is illustrated in Figure 3.14. Most rate gyros are mounted remotely.

The torque on the rotor axis can be sensed in two ways. The conventional method requires the rotor to be restrained by a spring (see Figure 3.14). When a torque is applied by the aircraft, the tendency for the rotor to precess deflects the spring. The amount of deflection is proportional to the rate of aircraft rotation. This deflection causes a small lamp mounted on the gimbal to sweep across a photosensitive potentiometer, resulting in an output voltage which is proportional to the angular rate of the aircraft. An exploded view of such a rate gyro is shown in Figure 3.15.

The second method is to rigidly fix the rotor axis to the housing and put sensors similar to strain gauges on the rotor shaft. This is referred to as a "flex gyro." It uses no gimbals and is more reliable because it has one less degree of freedom than the conventional rate gyro.

No meaningful comparison of cost, weight, and failure data of gyros can be made.

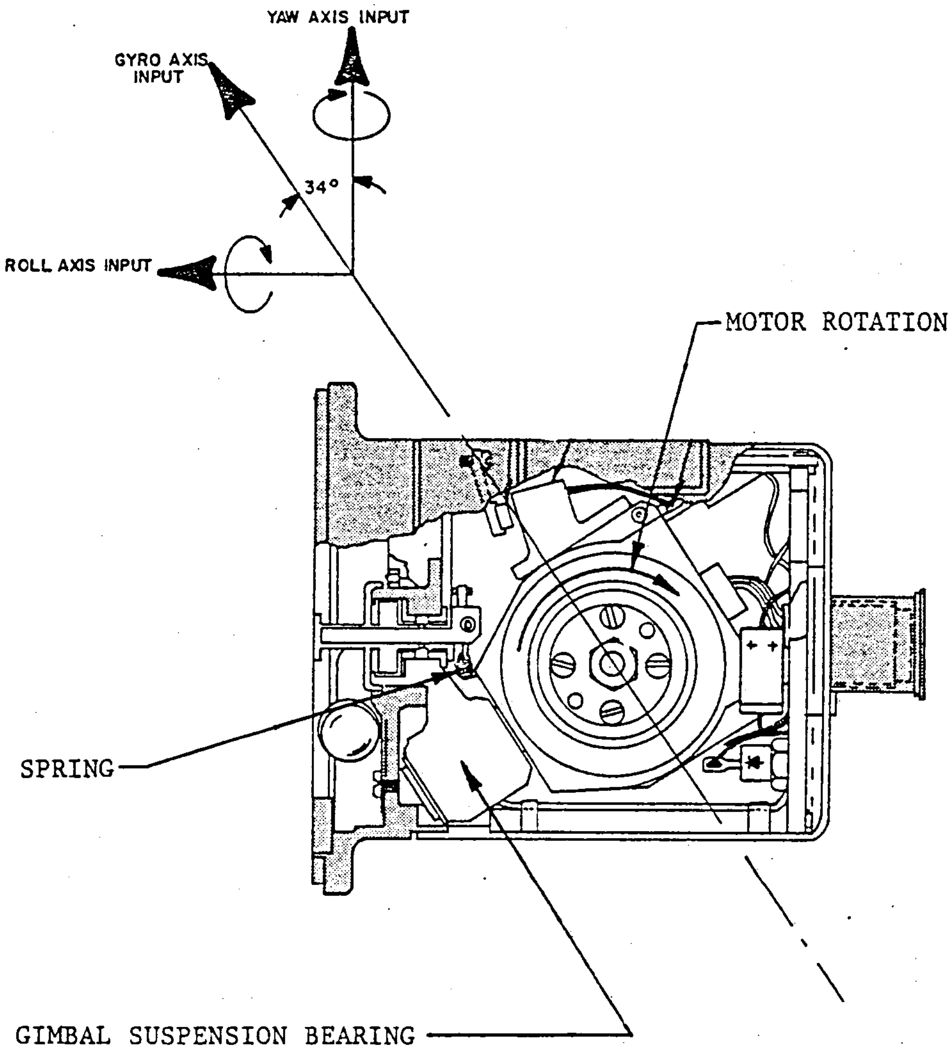


Figure 3.14. - Tilted rate gyro
(Reference 10).

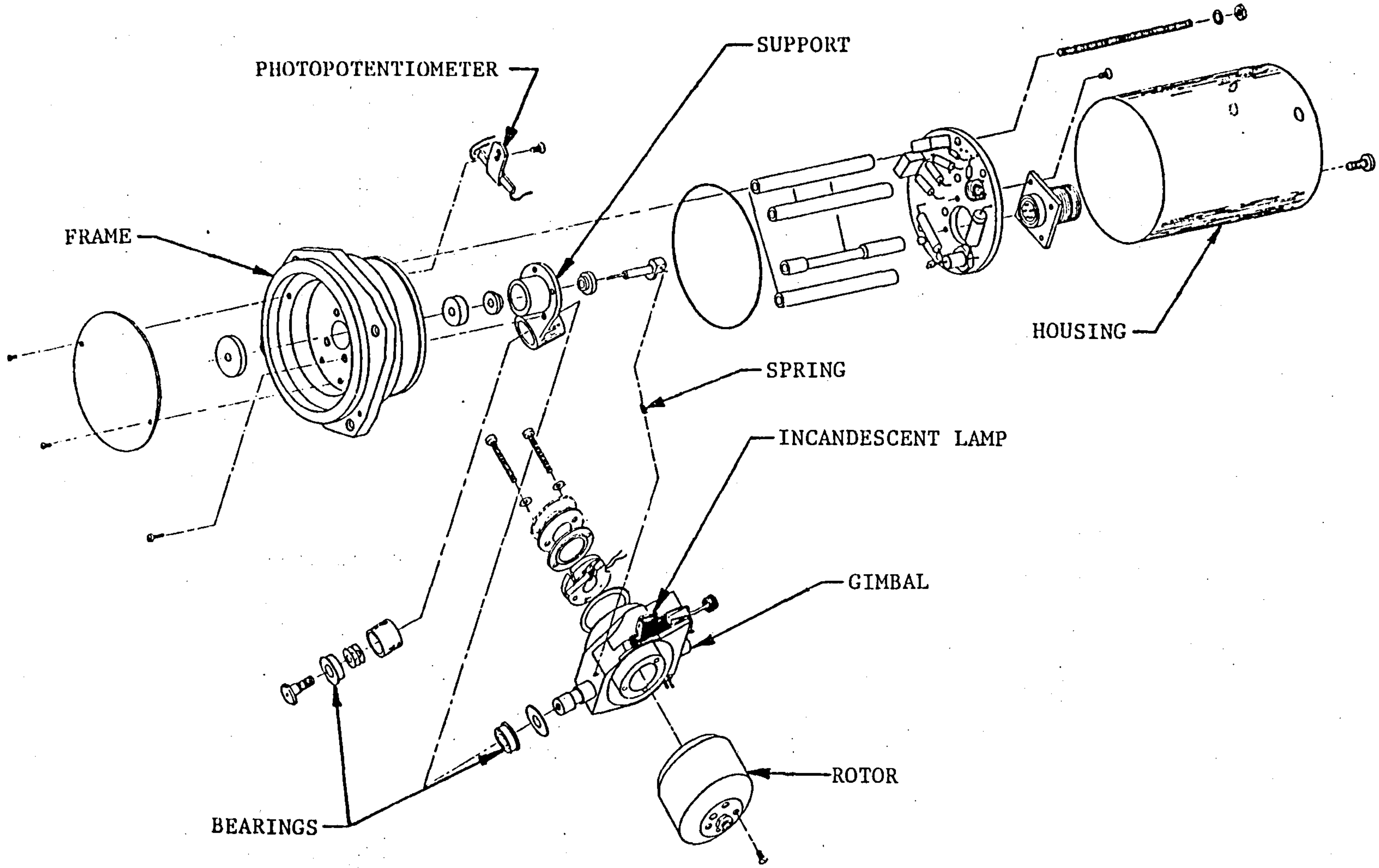


Figure 3.15. - Rate gyro, exploded view
(Reference 10).

3.3.4.1.2 Altitude Sensors.- Altitude sensors are available in two main forms:

1. Bellows
2. Oscillating cylinder

The most common altitude sensor is the bellows altimeter. Altitude changes are converted to electrical signals for the autopilot via a potentiometer interfaced with the side of the bellows. As altitude is increased, the volume of the bellows increases. This moves the slide on the potentiometer, generating an output which is proportional to the change in altitude. A pressure transducer uses a variation on this method and can be used to sense altitude also. A flexible diaphragm separates a chamber of reference pressure from one exposed to ambient pressure. A strain gauge mounted to the diaphragm produces an output voltage as the diaphragm deforms.

A so-called "oscillating cylinder" is a new sensor used by one company on an IFCS. The device works on the principle that the natural frequency of a vibrating cylinder will change if the air pressure inside the cylinder changes relative to the outside. This device is discussed in greater detail in Reference 12.

3.3.4.1.3 Airspeed Sensors.- Very little variation in airspeed sensors exists presently. Pitot-static systems are still in widespread use as airspeed sensing devices. Several alternatives have been suggested, however, and are referenced in Paragraph 3.3.4.2. No other information about other current airspeed sensors was available.

3.3.4.2 Advanced Sensors

In general, there is a trend toward solid state transducers which is aimed at eliminating moving parts and improving the reliability of state-of-the-art sensors. Brief descriptions of some of these follow.

The application of fluidics to GA aircraft instrumentation and control in general has shown promise in the past, and the benefit to sensor technology is potentially great. Many specific applications are described in detail in References 13 and 14.

A technological advancement known as the laser gyro could eventually be applied to general aviation. Briefly, laser gyros are composed of two beams of laser light rotating in opposite directions in a closed triangular circuit. As the unit is rotated, the frequencies of the beams become unequal by an amount that is proportional to the rate of rotation. This change in frequency is measured by the instrument. In this sense, it performs the same function as a rate gyro but has no need for rotors, gimbals, or other moving parts. More detailed descriptions of laser gyro systems can be found in References 15 and 16. Some of the advantages of laser gyro systems are these:

1. Low alignment time
2. High reliability
3. Low operating power
4. Digital output

Presently, laser gyro systems are prohibitively expensive for GA application. However, the projected MTBF of a laser gyro is 85,000 hours.

3.3.5 Actuators

Actuators are used to deflect control surfaces as commanded by the auto-pilot to obtain the desired airframe response. By far, the most common method used in general aviation is conventional electromechanical servos coupled to the aircraft's primary flight control system. Other conventional methods of actuation are pneumatic and hydraulic, although the latter is rarely used in general aviation. These actuators, along with other proposed actuation devices, are discussed in the following.

3.3.5.1 Conventional Actuators

As stated earlier, the most common method used for control surface actuation is the electromechanical servo. A typical servo/capstan assembly with representative dimensions is shown in Figure 3.16. The main components of the

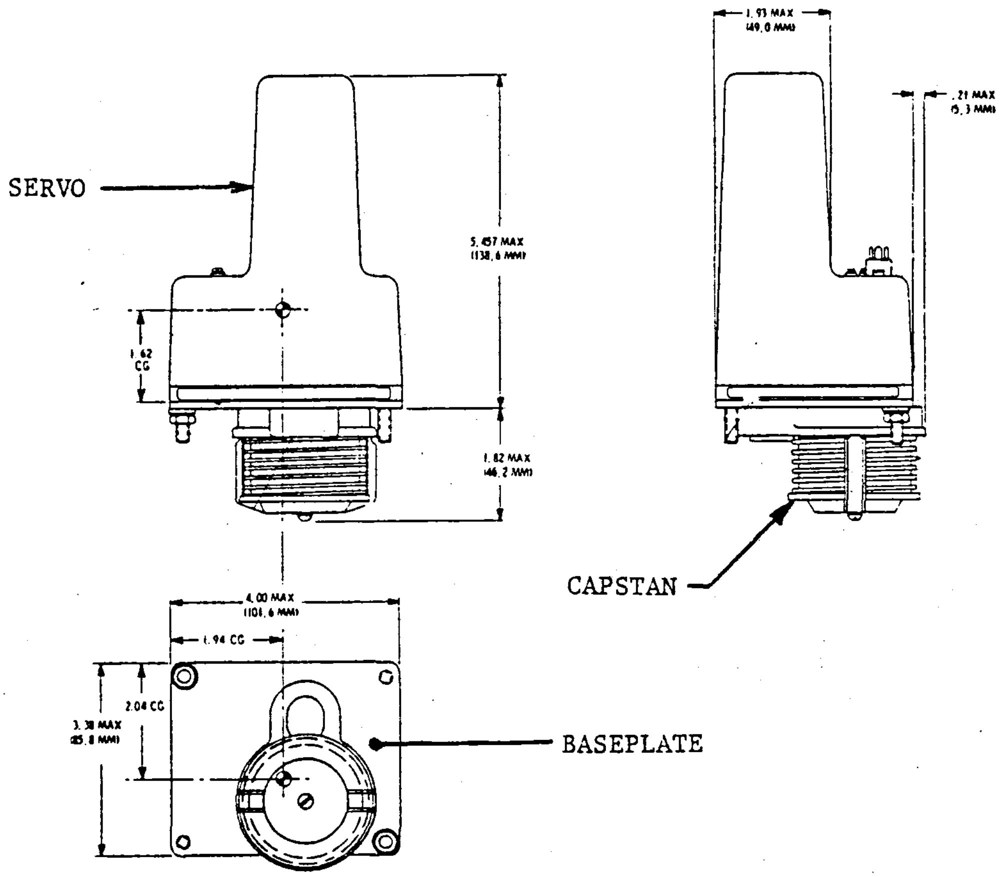


Figure 3.16. - Typical electromechanical actuator (Reference 17).

assembly are the servo, capstan, and baseplate. The servo drives the capstan, which is attached to the primary flight control system. The actuator can be overridden by the pilot through the slip clutch (not shown). The slip clutch is housed between the capstan and the drive pinion and can be set to slip at a preselected torque. Thus, if the servo has failed so that it is driving without the proper command, the pilot can override it by applying a force to the controls that is great enough to produce a torque on the capstan which is greater than that set into the slip clutch. Some servos employ electrical torque-limiting circuits.

Servo-output torques can range anywhere from 50 to 150 in-lb, while motor break frequencies usually run in the neighborhood of 3 Hz. This high frequency is required for quick servo response and, therefore, crisp autopilot control.

The internal components of an electromechanical servo are shown in Figure 3.17. When energized, the engage solenoid pivots the motor/pinion assembly to interface the pinion (not shown) with the slip clutch and, hence, the capstan. If electrical power is lost, the spring disengages the pinion from the slip-clutch. The tachometer senses motor speed through a gear train and feeds the signal back to the computer to stabilize the servo.

Typical installations of a primary and trim actuators are shown in Figures 3.18 and 3.19, respectively. With a primary actuator, the capstan is fixed to the primary control cable through a bridle cable. The bridle cable is wrapped around the capstan while the ends are calmped to the primary cable. The trim actuator transmits force to the primary cable via an idler pulley. The baseplate allows the servo to be disconnected from the capstan assembly, so that the capstan does not have to be disconnected from the primary control cable for maintenance.

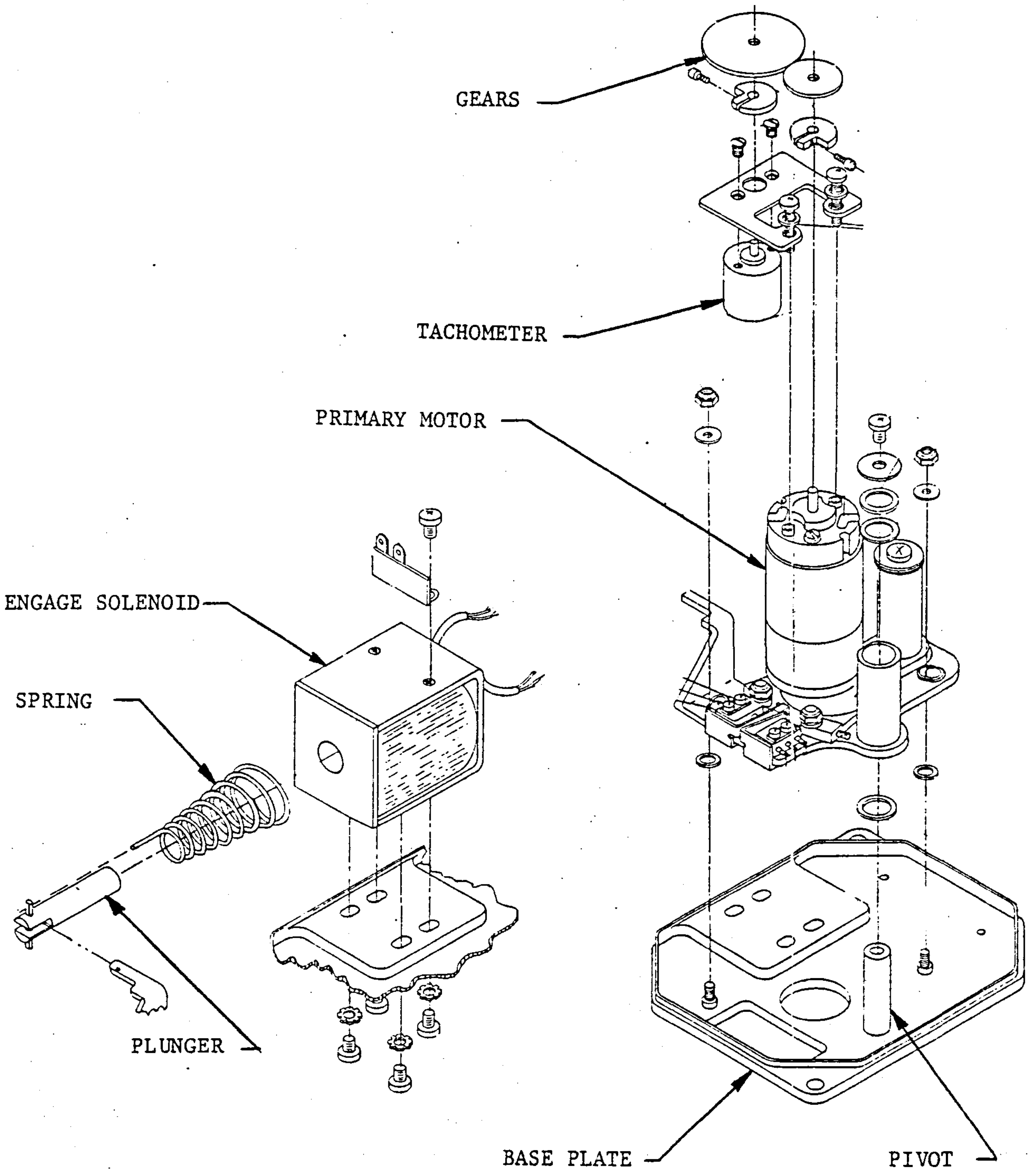


Figure 3.17. - Exploded view of electromechanical servo (Reference 18).

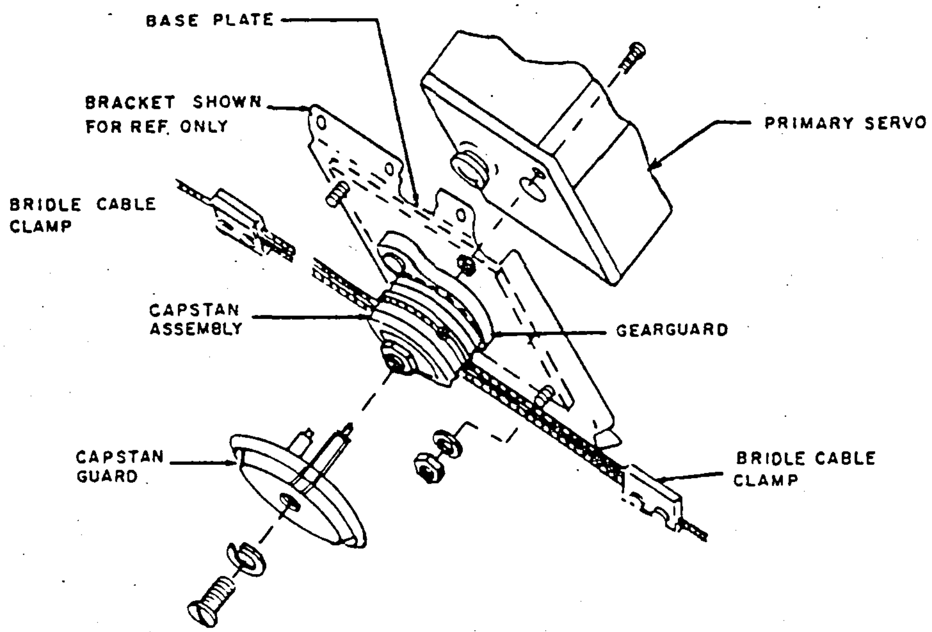


Figure 3.18. - Typical primary actuator installation (Reference 17).

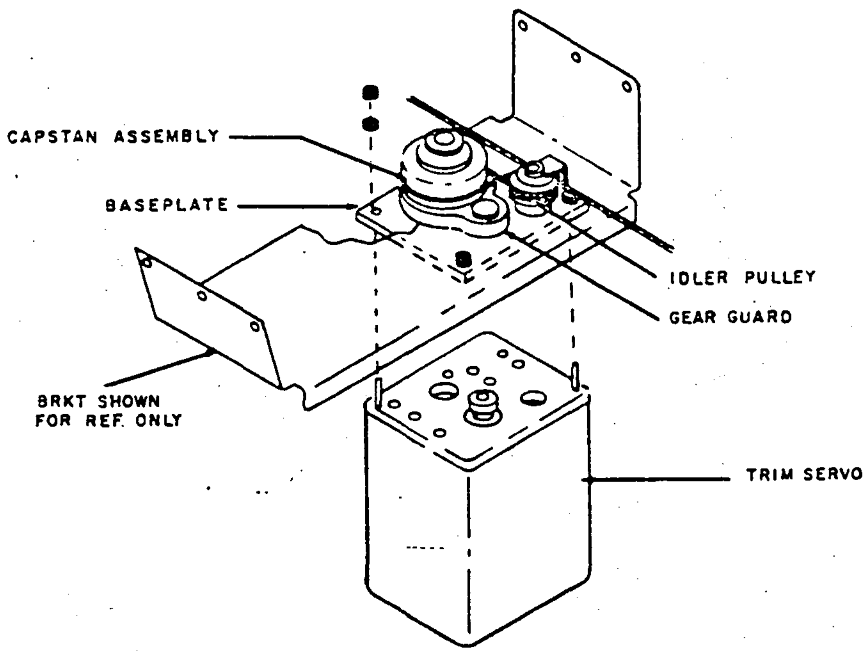


Figure 3.19. - Typical trim actuator installation (Reference 17).

Trim servos are designed to output approximately 20 - 70 in-lbs for an indefinite period of time. They must also have a high output speed in order to keep the aircraft trimmed to minimize the load on the primary actuator as the aircraft enters into new attitudes. However, if the trim system is too fast, a runaway trim condition can lead to overstressing of the airframe if the pilot is not made aware of it. This is possible because the autopilot will mask the fact that the airplane is out of trim with the primary control surface. Then, if the autopilot is disengaged or the slip clutch of the primary actuator is finally overridden, a violent maneuver could occur. FAA certification procedures (see Chapter 4) dictate that, after any failure, the pilot must wait three seconds after he recognizes the failure before taking any corrective action. Then, the airplane cannot exceed a 0 to 2 g envelope during recovery. This could be difficult during a trim-runaway failure. Thus, manufacturers have either limited trim servo speed, which compromises performance, or incorporated trim-failure detection and annunciation. In the latter case, the pilot can start counting the three seconds after annunciation, which can be long before a violent maneuver will occur. Criteria for failure include the following: trim movement with no trim command, trim command and no trim movement, or trim servo drive in the wrong direction. The detect circuitry can be included in the computer or actuator. Failure annunciation allows higher trim speeds to be used. Trim speed can also be tailored to the airframe and to the flight condition (e.g., flap switch to speed-up trim on approach).

Three types of pneumatic actuators are shown in Figure 3.20. The diaphragm type is the only one in use. The output force is equal to the supply pressure multiplied by the piston area. This pressure is controlled with valves actuated by signals from the computer. The air to drive the actuator

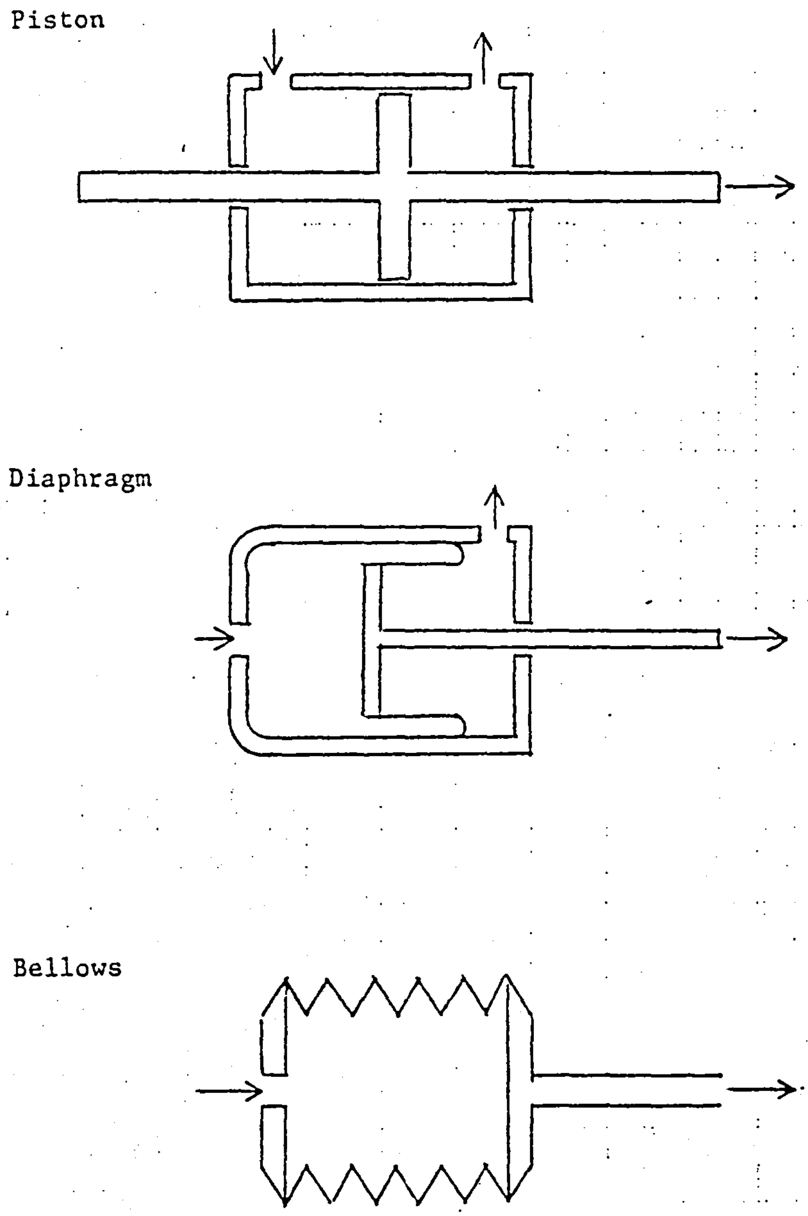


Figure 3.20. - Pneumatic actuator types
(Reference 19).

comes from an engine-driven air pump. Like the electromechanical actuator, the pneumatic servo attaches to the flight control cables present in the aircraft.

Two types of hydraulic actuators are shown in Figure 3.21. Higher system pressures make the size of the hydraulic actuator smaller than a pneumatic actuator. Hydraulic actuators are comparable to electromechanical actuators in size and performance, but the overall system weight tends to prohibit their use in light airplanes, although some business jets use hydraulic systems. A typical primary surface installation is shown in Figure 3.22.

All of these actuators are discussed in detail in References 19 and 20. Typical transfer functions of electromechanical and hydraulic actuators can be found in Reference 2, Chapter 10.

3.3.5.2 Advanced Actuators

In recent years, much research has been performed in the area of rare earth, samarium-cobalt-electric motors. These motors are lighter, faster, and smaller than their conventional counterparts. Figures 3.23 and 3.24 illustrate the small dimensions and high break frequency of samarium-cobalt motors. The magnetic characteristics of these motors allow the use of an "inside out" design. Here, the permanent magnet is in the rotor and the windings are in the stator. This eliminates the need for moving mechanical/electrical contacts, and the commutation can be done electronically. In addition, the volumetric efficiency of samarium-cobalt magnets allows smaller rotor size and thus higher speeds. The brushless design is also more reliable.

Two types of installation are possible with samarium-cobalt electromechanical actuators. One of these is shown in Figure 3.25. With this installation, space is conserved by having the gearbox act as the hinge for the control sur-

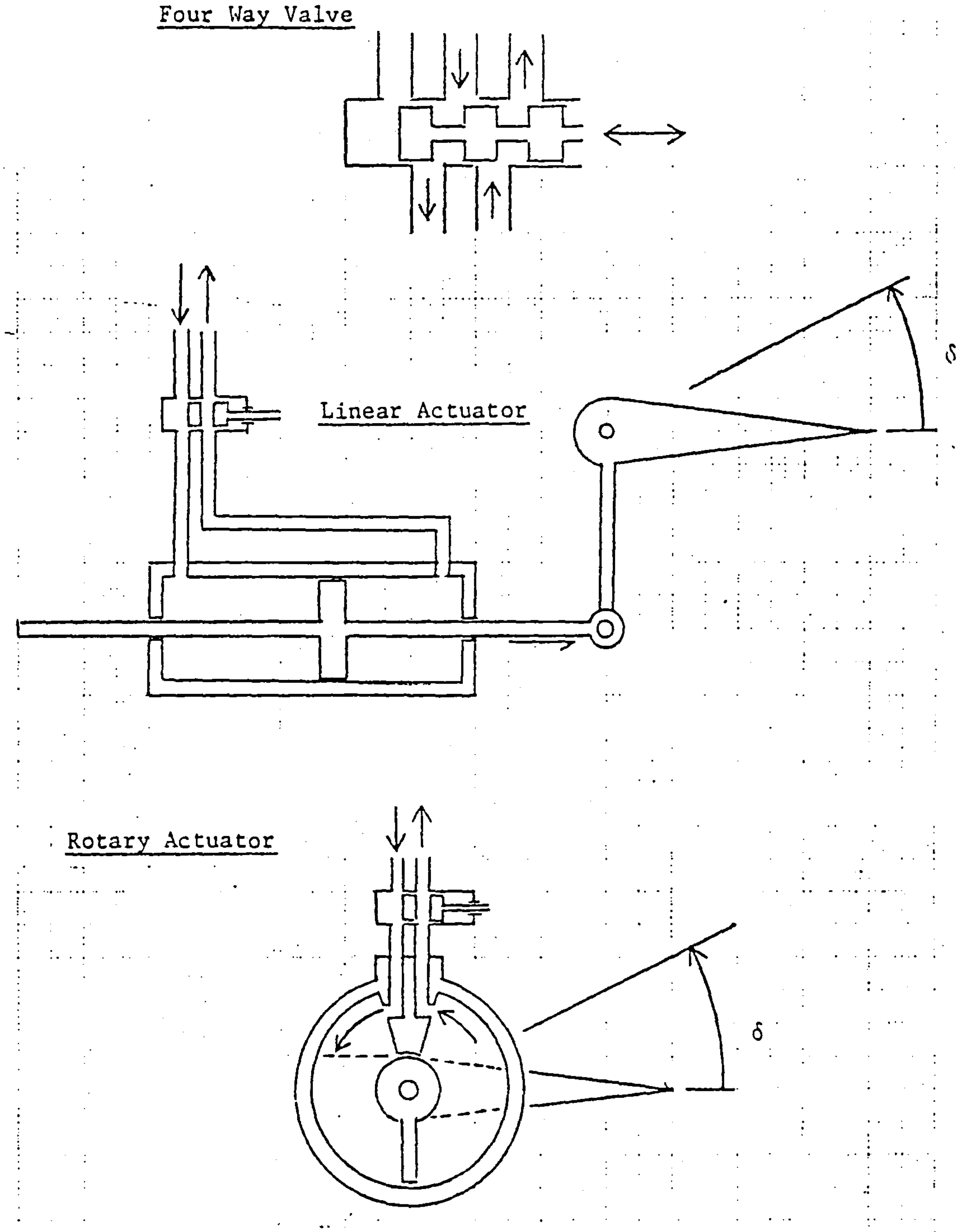


Figure 3.21. - Hydraulic actuator types
(Reference 19).

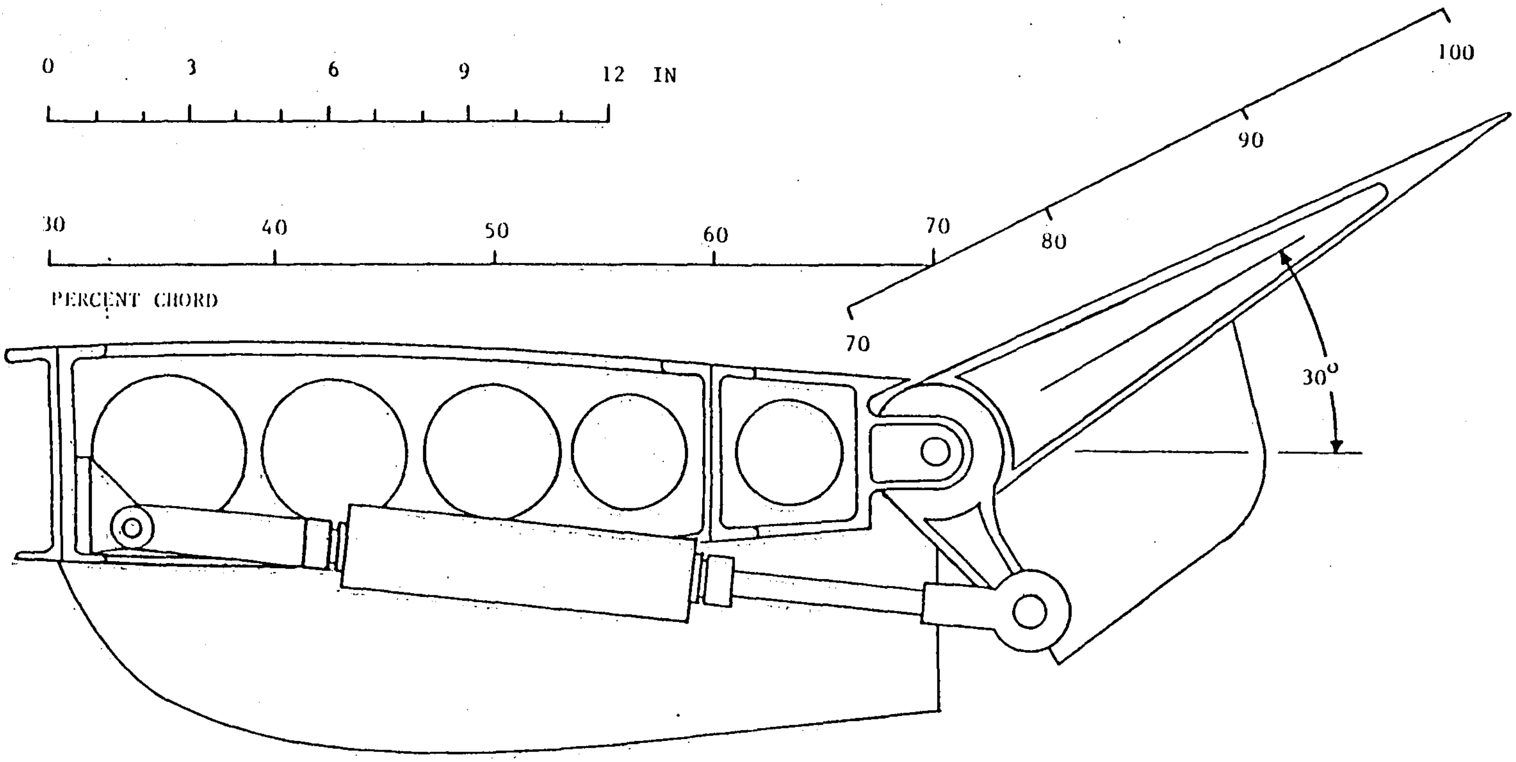


Figure 3.22. - Hydraulic actuator installation
(Reference 20).

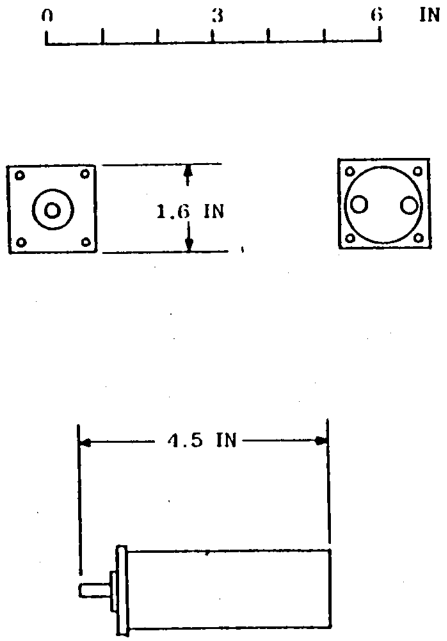


Figure 3.23. - Samarium-Cobalt motor (Reference 20).

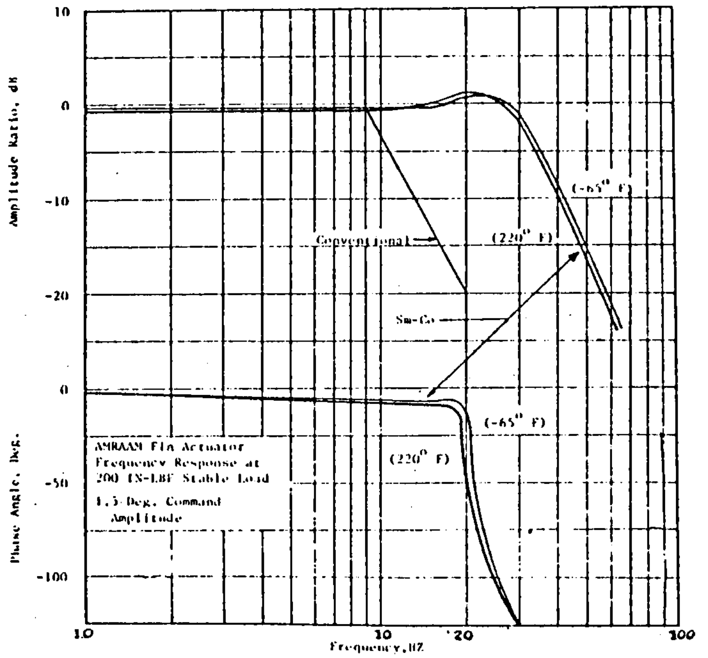


Figure 3.24. - Frequency response characteristics of Samarium-Cobalt and conventional actuators (Reference 20).

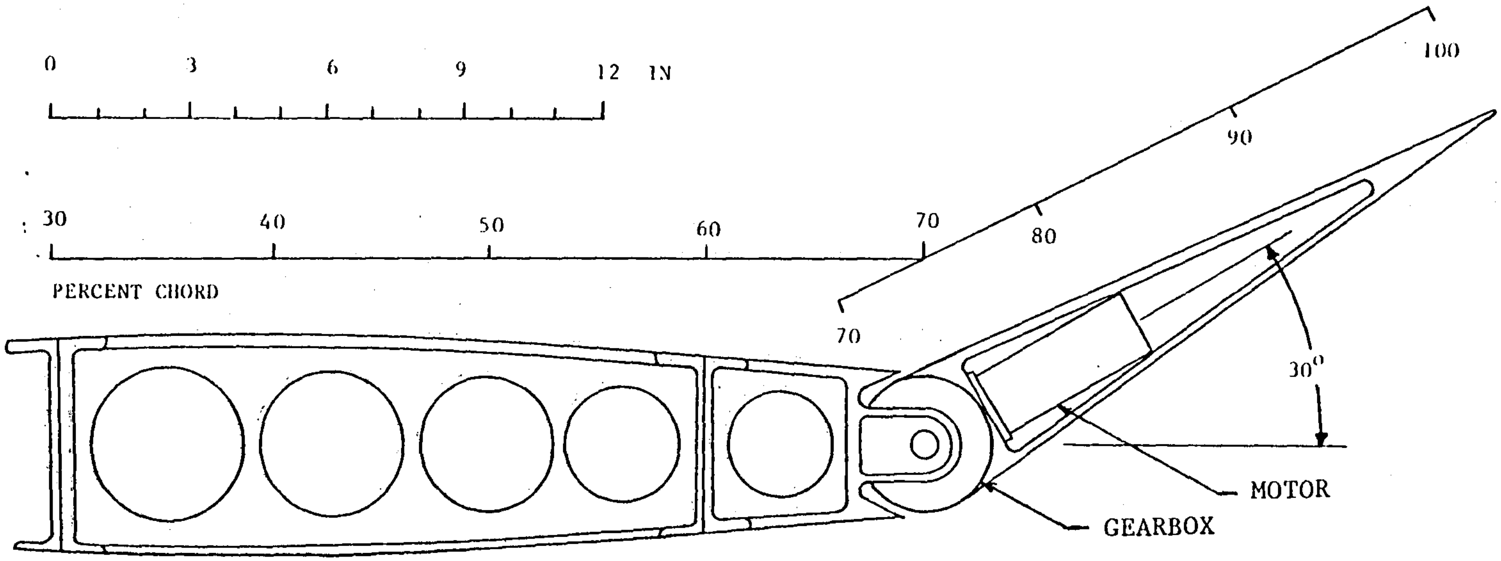


Figure 3.25. - Gearbox-hinge installation concept
(Reference 20).

face. This installation would only be practical as part of the original aircraft design.

The second configuration is illustrated in Figure 3.26. Here, the rotor axis coincides with the hingeline of the surface for a further reduction in volume. Again, this actuator would be difficult to retrofit to an existing airframe and is more practical as a primary flight control device.

These actuators are compared with pneumatic and hydraulic designs in Reference 20. Reference 21 discusses in detail the application of samarium-cobalt electromechanical actuators. Table 3.7 summarizes typical actuator characteristics. It should be remembered that these are only representative examples.

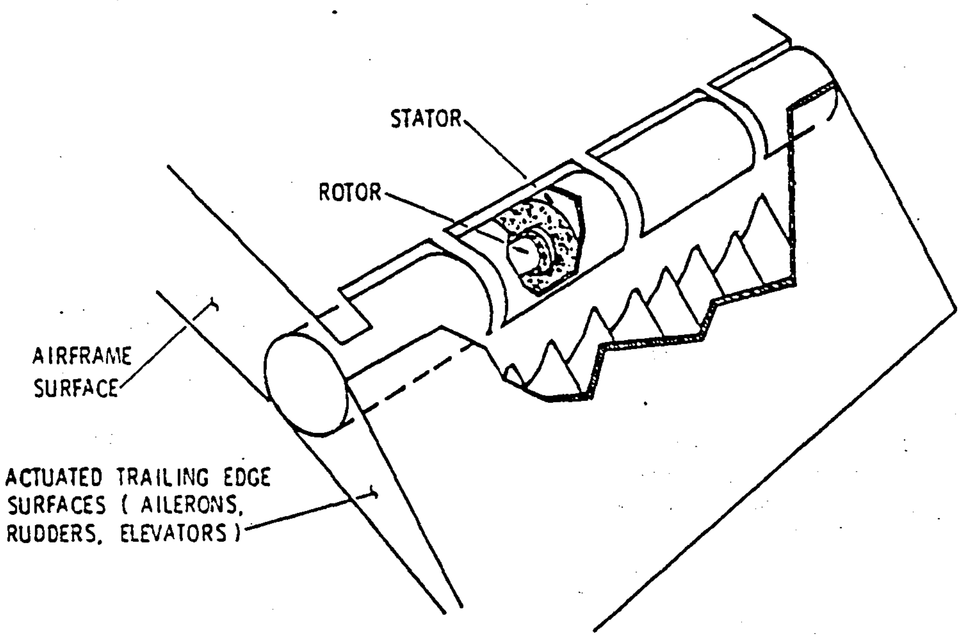


Figure 3.26. - Integrated motor/hinge installation concept (Reference 21).

TABLE 3.7. TYPICAL ACTUATOR CHARACTERISTICS

Character-istic	Type: Standard Electro-mechanical	Sm-Co Electro-mechanical[a]	Pneumatic[b]	Hydraulic[b]
Weight	1.6 kg	0.5 kg	3.4 kg	1.5 kg
Volume	$2.0\text{x}10^{-3}$ m^3	$2.0\text{x}10^{-4}$ m^3	$4.0\text{x}10^{-3}$ m^3	$8.0\text{x}10^{-4}$ m^3
Price	$600	N/A	N/A	N/A
Output	50 - 150 in-lbs (capstan) 7 - 64 rpm No load	9.6 in-lb 14,000 rpm No load	N/A	N/A
Input	28 or 14 VDC	28 or 14 VDC	$7.0\text{x}10^{5}$ Pa	$3.5\text{x}10^{6}$ Pa
MTBR	1350 hrs	N/A	N/A	N/A

[a]Data is for motor only.

[b]Support systems not included.

With the trend toward digital autopilots, it is predicted that stepper motors will be used in actuators to eliminate the need for digital-to-analog converters. These actuators are activated by digital impulses and can rotate in increments of as little as one degree per pulse. The direction of motion is commanded with a separate signal. The motor is always energized so that the actuator is rigidly held in its last commanded position when no drive signal is present. Stepper actuators operate by position command, whereas most conventional actuators are driven by speed command (the output speed is proportional to the applied voltage). Because of this, stepper motors are not compatible with state-of-the-art autopilot computers, which use control-surface rate feedback for control.

3.3.6 Power Sources

Electrical (and, in one case, pneumatic) power is required to make the autopilot function properly. In all cases electricity was supplied by the aircraft's 14- or 28-volt battery system. Pneumatic power is generally obtained from a pump driven by the engine. Aircraft power sources have necessarily become standardized over the years so little variation exists. No research is being conducted in the area of aircraft power sources for general aviation, and it is industry's attitude that none is warranted. Also, the nature of aircraft power sources makes discussions of peformance and cost difficult.

3.3.7 Signal Transmission Media

Inherent in a system such as an autopilot is the need to exchange information between components. The major links are between the computer and the sensors, actuators, and mode selector/annunciator. Not surprisingly, these links are established with electrical wire, since the signals themselves are electrical. One system employs a pneumatic signal transmission network. Gyro gimbal displacement opens ports which allow air pressure to reach the appropriate servos.

Although no fundamental improvement has been made in electrical wire technology itself, recent advances in digital microprocessing has led to serial data bus transmission, also known as multiplexing. This is a method by which a number of signals in various forms can be sent on the same line, which means that few wires are needed. This will become a standard feature as digital autopilots evolve.

Fiber optics have the potential to replace electrical wire between components in autopilots, but the cost is generally considered to be prohibitive for general aviation. No research is being done to apply this technology to GA.

3.4 AUTOPILOT MODES AND FEATURES

General Aviation autopilots can come equipped with many modes and features depending on the specific needs of the buyer. Most autopilots begin with the basic modes such as attitude hold, heading hold, and altitude hold. Altitude and heading preselect are also offered. Radio (VOR, Localizer, and Glideslope) coupling is common, with both tracking and capture capabilities available. Other additional modes include indicated airspeed (IAS) hold, vertical speed hold, Mach hold, and back course capability on a localizer beam. Some autopilots include any or all of the following features: turn and pitch command, control wheel steering (or pitch synchronization), automatic pitch trim, go-around, automatic turn coordination, testing capability, and failure detect and annunciation. Each mode and feature is discussed below with emphasis on principles of operation, equipment required, and initiation or utilization procedures.

It should be remembered that a wide variety of methods for incorporating these modes and features into GA autopilots exists today. It is beyond the scope of this report to describe all in detail. Only the most common methods will be discussed to give the reader a basic idea of what modes and features are available and how they function. For more detailed and analytical descriptions the reader is directed to Reference 2, Chapter 13.

3.4.1 Basic Modes

3.4.1.1 Attitude Hold

Attitude hold is accomplished by sensing a deviation from the desired position and then deflecting the proper control surface so as to oppose the undesired attitude deviation. A vertically oriented gyroscope is usually used to measure both roll and pitch displacement. A signal is produced and sent to the autopilot computer, where it is amplified and routed to the proper actuator to deflect the control surface by an amount proportional to the displacement. Elevator deflection is either measured directly or determined by sensing the actuator deflection. A typical block diagram for a pitch attitude hold mode is shown in Figure 3.27.

One manufacturer implements pitch attitude hold without the use of a gyroscope. The system was designed under the assumption that any variation in airspeed is indicative of a change in pitch attitude (all other factors are apparently assumed constant). Thus, the system senses only variations in airspeed through the pitot-static system, and subsequently commands the elevator servos to correct the error. With this method, the aircraft must be trimmed before the autopilot is engaged.

Most autopilots automatically engage the attitude hold modes when they are turned on. The pilot maneuvers the airplane to the desired roll (or pitch, if so equipped) attitude and then engages the autopilot. The airplane will then maintain that attitude.

3.4.1.2 Heading Hold

Heading hold can be implemented in three ways. The conventional method is to use a directional gyro (DG) to sense yaw displacement. Then, as with

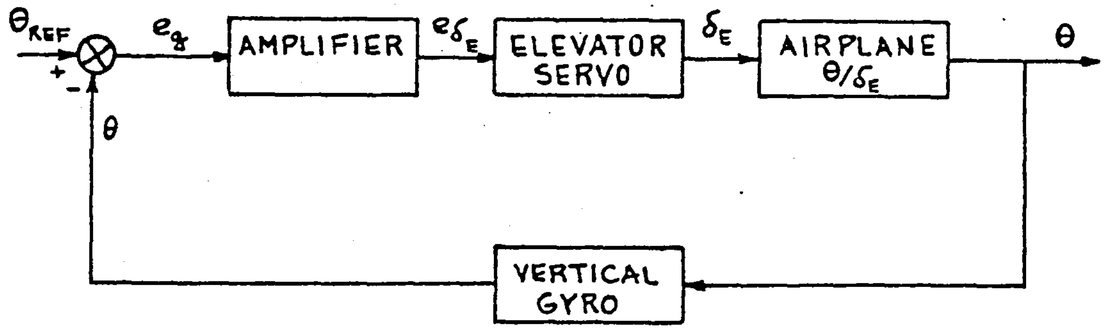


Figure 3.27. - Attitude hold block diagram
(Reference 2).

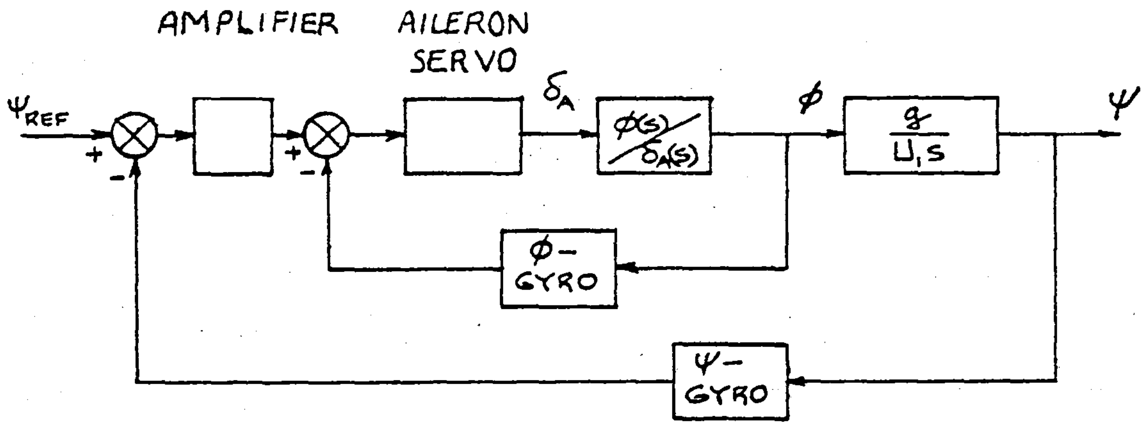


Figure 3.28. - Block diagram of heading hold with
inner loop roll rate damping
(Reference 2).

attitude hold, the signal is sent to the autopilot computer and an output signal is sent to the aileron actuator to produce a turn rate proportional to the heading error. This is usually combined with an inner, bank-angle control loop because of the relationship between bank angle and rate of change of heading. A typical block diagram for a heading hold mode is shown in Figure 3.28. At least one manufacturer uses a rate gyro to sense yaw rate, integrate it over time to obtain heading error and send the resulting signal, via the computer, to the actuator. The third method of heading hold uses a magnetic heading sensor to determine the aircraft's orientation relative to the earth's magnetic field. This system merely senses the deviation between the magnetic heading of the airplane and the reference magnetic heading. This is done using an electronically pulsed Earth magnetometer.

Heading preselect is possible with a DG or magnetic sensor. With a DG, the reference direction is preselected with the heading bug on the horizontal situation indicator. The bug is moved to show the desired direction. Once the heading preselect button is pushed on the mode selector, the autopilot commands a constant rate turn until the direction shown by the heading bug coincides with the airplane heading, whereupon the heading hold mode is automatically engaged. If the system uses a magnetic heading sensor, the autopilot is not connected to an HSI. A separate azimuth card, located on the autopilot controller, is used to perform the function of the heading bug (see Figure 3.29).

3.4.1.3 Altitude Hold

Altitude hold simply keeps the aircraft at a constant altitude via elevator control. Pressure altitude is generally used for this mode, and it is sensed using a bellows altimeter. This mode functions in basically the same manner as the other hold modes in that an error signal is sent from the sensor

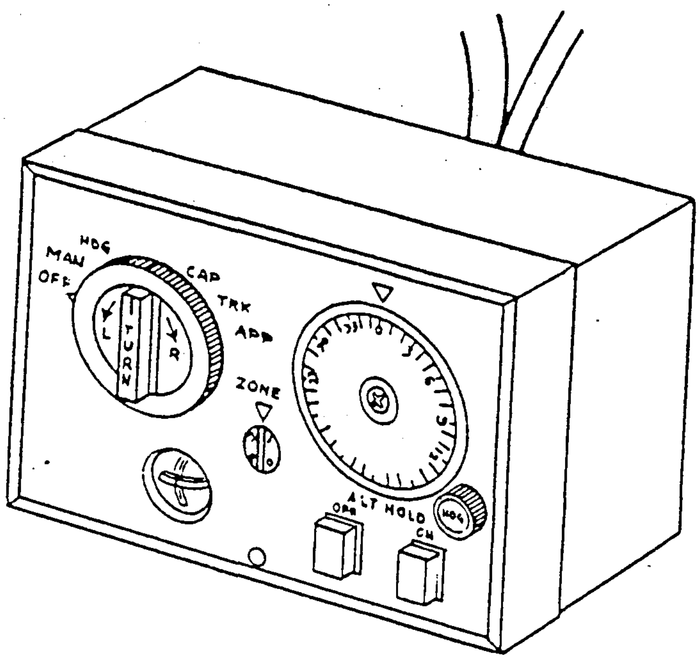


Figure 3.29. - Autopilot controller with heading hold azimuth card (Reference 22).

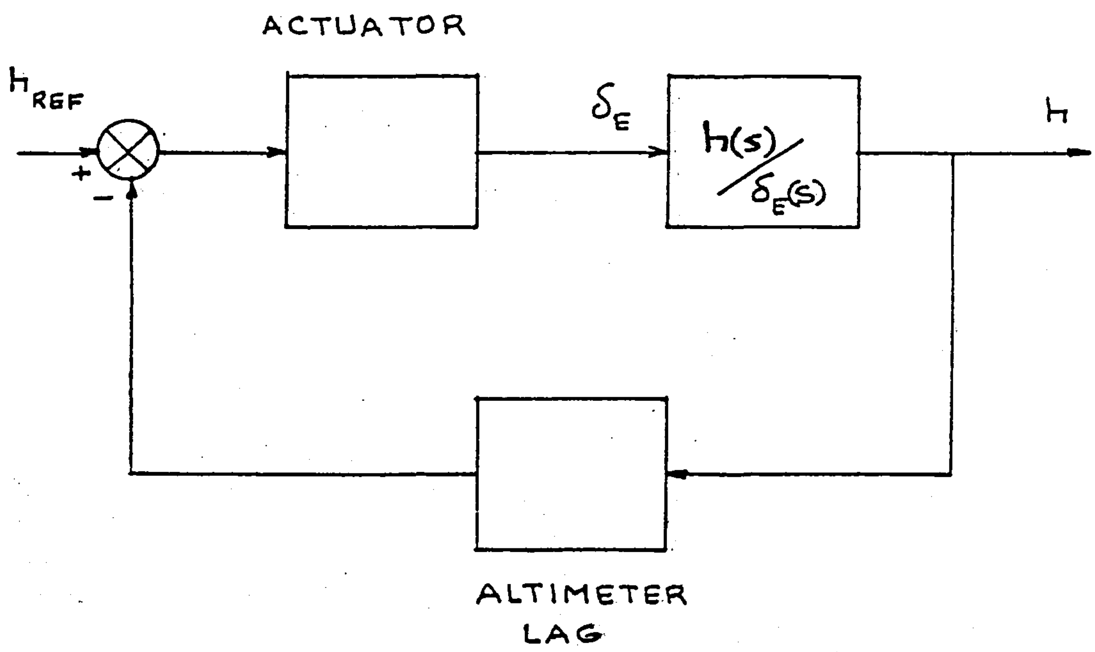


Figure 3.30. - Altitude hold block diagram (Reference 2).

to the computer where it is processed, whereupon a command is sent to the control surface actuator to nullify the error. A block diagram for a typical altitude hold mode is shown in Figure 3.30.

Altitude preselect is also available on some GA autopilots. This feature operates by initiating a constant rate of climb or descent (using only elevator commands) until the desired altitude (entered into the system through a keyboard or dial) is achieved, at which time the hold mode is automatically engaged.

3.4.2 Additional Modes

3.4.2.1 Radio Coupling

Many autopilots have the capability to track a VHF omnidirectional range (VOR) and/or localizer (LOC) beam. In these modes, the error signal is the angular deviation of the aircraft from the center of the beam with respect to the transmitter. To track the beam, the autopilot simply maneuvers the aircraft to nullify this error. The geometry for a VOR/LOC track mode is shown in Figure 3.31, while the block diagram is illustrated in Figure 3.32. The angular error signal is sent to a coupler which determines the appropriate heading required to return the aircraft to the center of the beam. This heading is maintained by the heading angle control system, which produces a new error angle via the "geometry transfer function box." This new error is sensed by the VOR/LOC receiver and fed back through the system. The vast majority of autopilots with this mode incorporate various forms of automatic crosswind correction.

VOR/LOC capture modes are also commonly available. This mode functions by commanding a constant heading to intercept the beam. Some autopilots require a 45° intercept angle, while others are capable of intercepting at a range of

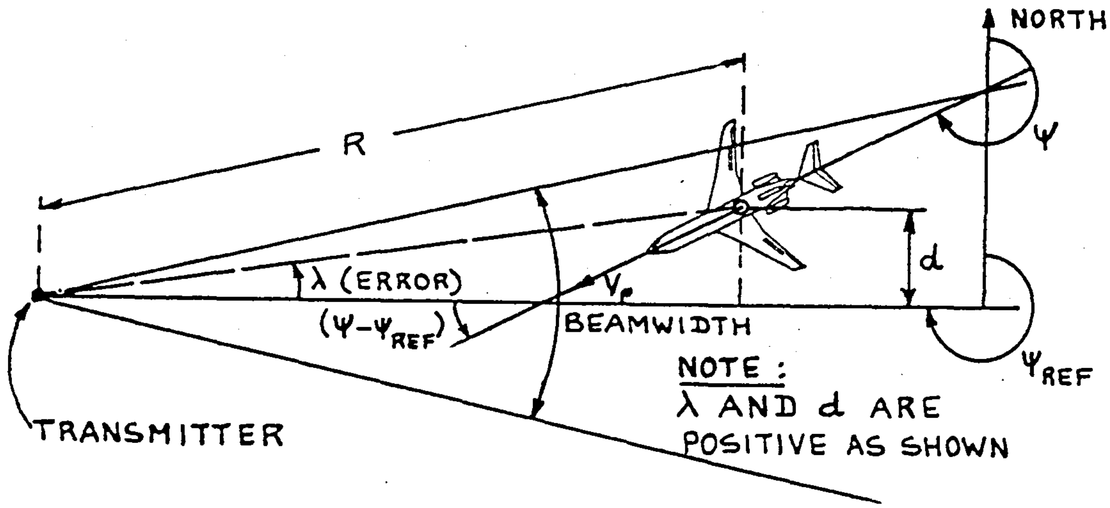


Figure 3.31. - Geometry for the analysis of a lateral beam intercept and hold mode (Reference 2).

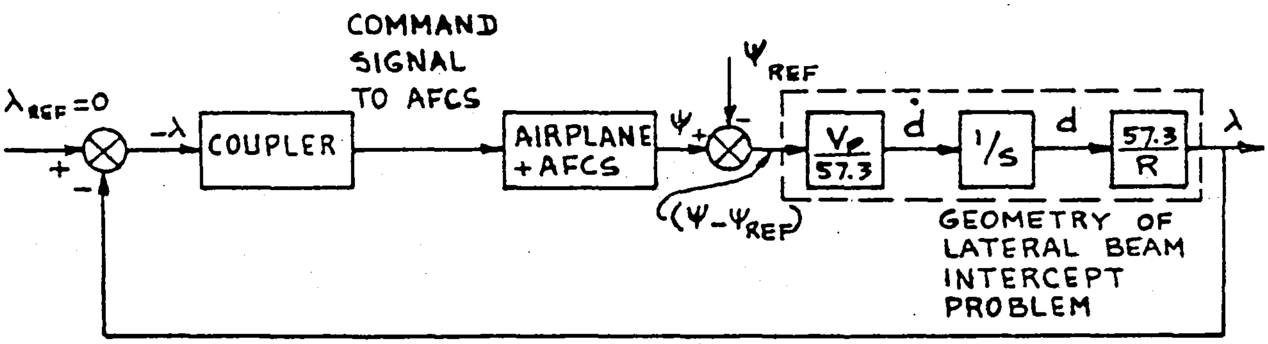


Figure 3.32. - Block diagram of a lateral beam (VOR/ LOC) hold (Reference 2).

angles. Many of the latter turn the aircraft to a 45° intercept angle at a certain distance from the beam. Once the center of the beam is crossed, most autopilots command a constant rate turn until the aircraft heading is parallel to the beam. At this point, the track mode is automatically engaged, and the aircraft follows the beam as described above.

It can be seen in Figure 3.31 that for a given displacement, d, the error angle, λ, increases as the transmitter is approached. Since the heading command is proportional to λ, heading instabilities can result near the transmitter. It is for this reason that many autopilots reduce the gain of the system gradually as the aircraft nears the VOR transmitter. This gain "scheduling" requires distance measureing equipment (DME) which can significantly add to the cost of the autopilot. When tracking a localizer, the gain is reduced over the middle marker.

Another problem is the erratic signal that is produced by a VOR station in the region directly above it, commonly referred to as the "cone of confusion." Most autopilots automatically engage heading hold upon entering this area, to prevent the aircraft from following this signal.

Many autopilots come equipped with a reverse, or "back course" mode. This automatically computes and performs the maneuvers necessary to follow a reverse course on a localizer beam. This allows the pilot to capture a localizer beam in the outbound direction and then reverse course and recapture the beam--all automatically.

Several autopilots also have the capability to track a glideslope beam. The principles involved in capturing and tracking a glideslope beam are very similar to VOR/LOC. The major difference is that the angle of intercept is very shallow. Some systems allow capture from above or below, while others are only capable of capture from below. A glideslope tracking system must have pitch attitude control capability.

3.4.2.2 Airspeed

Another common longitudinal mode is indicated airspeed (IAS) hold. Pushing the IAS hold button on the mode controller will cause the aircraft to maintain the airspeed indicated at that time. Many autopilots intended for business jets have an altitude switch so that above a certain altitude, often 8839 m (29 000 ft), Mach number is held constant rather than IAS. To hold airspeed, the pitot tube must be interfaced with the autopilot computer so as to command elevator deflection when airspeed changes. Mach number hold is similar, but a Mach sensor or air data computer is necessary to determine Mach number from IAS and ambient air temperature. Block diagrams for typical airspeed and Mach hold modes are given in Figures 3.33 and 3.34, respectively.

Since airspeed hold operates through the elevator, it cannot be operated in conjunction with altitude hold and attitude hold. Most autopilots equipped with IAS and altitude hold will automatically disengage one mode if the other is activated. Complete control of all three modes at once is possible with the installation of an autothrottle (or auto-drag)*, but none of the autopilots surveyed were so equipped.

Vertical speed hold is another mode some advanced autopilots perform. With an air data computer, altitude can be determined at regular intervals and then differentiated to obtain vertical speed. This value is compared to the desired value (that which was present or preselected at the time the mode was engaged), and the error is sent to the autopilot computer which commands the proper elevator deflection. It is possible to measure vertical speed using a pressure chamber which uses a "calibrated leak" to sense rate of change of altitude.

*See Reference 2, Chapter 13.

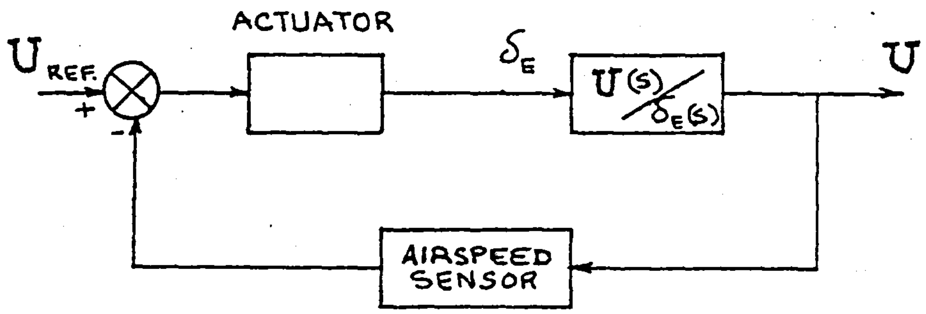


Figure 3.33. - Airspeed hold block diagram
(Reference 2).

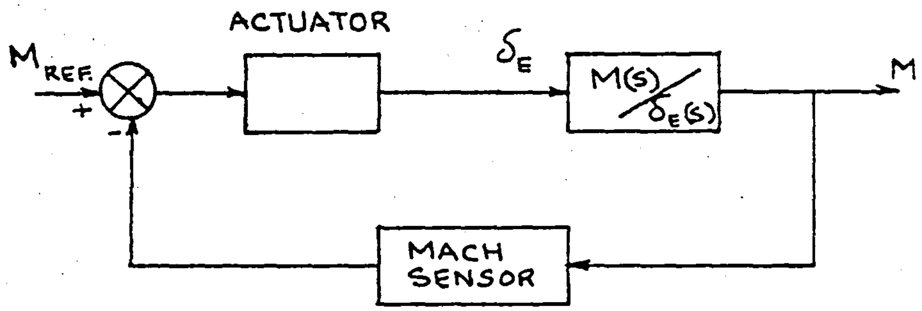


Figure 3.34. - Mach hold block diagram
(Reference 2).

;.3 Autopilot Features

Autopilots generally come with extra features which, while not being true des, warrant discussion.

Roll and pitch command knobs allow the pilot to change the reference attiıde without disengaging the autopilot. Thus the pilot can change heading or itch attitude very simply and smoothly. This command control can be of two asic types: displacement and velocity. The displacement type commands a spe:ific attitude angle proportional to that of the knob. The velocity type comıands an angular rate proportional to the displacement of the knob. The latter type usually has a spring which returns the knob to its center (zero rate) position when it is released by the pilot.

An alternative to command knobs is control wheel steering (CWS) or pitch synchronization. By depressing a button on the control wheel, the signals to the autopilot are interrupted. The pilot can then maneuver the aircraft to the desired attitude or heading. The pilot then releases the button, and the autopilot maintains the new attitude. Many autopilots are equipped with both command control and CWS to provide the most flexibility for the pilot. CWS can also be used to establish a new altitude if in the altitude hold mode.

Automatic pitch trim is a feature which can prolong pitch servo life and prevent an abrupt maneuver when the autopilot is disengaged. The object is to maintain a zero hinge moment on the elevator and thus zero torque on the servo. The most common method is to sense servo torque directly. One company employs a system that senses the current drain of the pitch servo and drives that to zero.

A go-around feature is often included in autopilots with pitch and roll axis control. When the pilot wishes to try again after a missed approach, the go-aroung function commands a wings level, pitch up attitude. The throttle must be advanced manually by the pilot. The button can be located either on the control wheel or on the throttle lever. Some companies will not allow the button to function until the throttles have been advanced.

Failure detection, annunciation, and automatic testing capability are features with widely varying capabilities. Virtually all autopilots have a test feature which illuminates the lamps on the mode annunciator. Some cycle through a test procedure which sends a signal through the autopilot computer circuits to determine if it is functioning properly. Others outline a pre-flight test procedure the pilot can perform manually. One model will self-test the computer and will not allow the autopilot to engage if there is a malfunction. In-flight failure annunciation is usually limited to actuator function. A "runaway trim" condition or insufficient voltage to a primary servo will activate a light on the annunciator panel dictating which servo is at fault. As systems progress more towards digital logic, test features are being expanded greatly.

Some sophisticated autopilots have a "fail passive" capability. This means that the autopilot automatically disables any channel or subsystem in which it detects a failure, and annunciates the failure to the pilot. More advanced autopilots are "fail operational," meaning the autopilot can detect a failure (most often an erroneous signal), annunciate it to the pilot, and switch in a back-up system or issue a dual command which effectively cancels the erroneous signal. With this feature, the autopilot can continue to be operated safely, with no loss of capability.

Automatic turn coordination is another feature that can be found on many

GA autopilots. With this feature, a coordinated turn can be initiated by turning a rotary knob located on the mode controller in the direction of the desired turn. The bank angle (and thus the rate, depending on the airspeed) of the turn is proportional to the deflection of the knob. To provide coordination, the ailerons must be coupled in some way to the rudder; and, therefore, a rudder actuator is required. An autopilot with this feature lends itself well to employing a yaw damper (Subsection 3.4.4) because the rudder servo is already provided.

3.4.4 Stability Augmentation

Most business jets and many twins require the addition of a yaw damper to improve stability. This system is usually separate from the autopilot. Sometimes dual yaw dampers are required, each having its own engage button, rate gyro, yaw computer, and rudder actuator. The system can be engaged independently of the autopilot. Since the yaw damper works to suppress yaw rates, the rate-gyro output must be washed out to prevent conflict with the pilot during a turn. This washout circuit assures that only transient yawing motions are damped. A typical yaw damper block diagram is shown in Figure 3.35.

In airplanes with poor inherent short period damping, especially at high altitude, a pitch attitude hold mode can further destabilize the aircraft. The addition of a pitch damper will correct this. A pitch damper works similarly to a yaw damper except that it will work through the autopilot computer already present. The addition of a rate gyro oriented to measure pitch rate, and a washout circuit to allow a steady pull up are necessary. A block diagram for a typical pitch damper is given in Figure 3.36.

It should be noted that simple pitch, roll, and yaw damping loops (in the form of rate feedbacks) are often incorporated as inner loops in attitude hold modes.

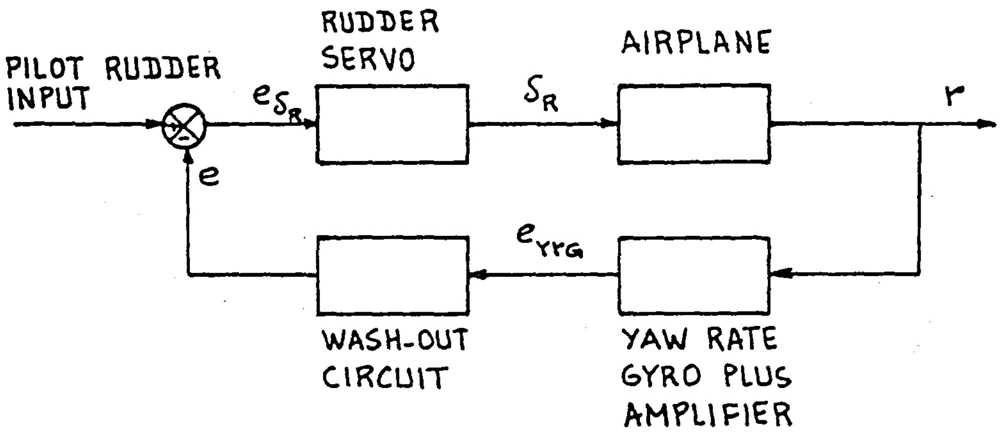


Figure 3.35. - Yaw damper block diagram (Reference 2).

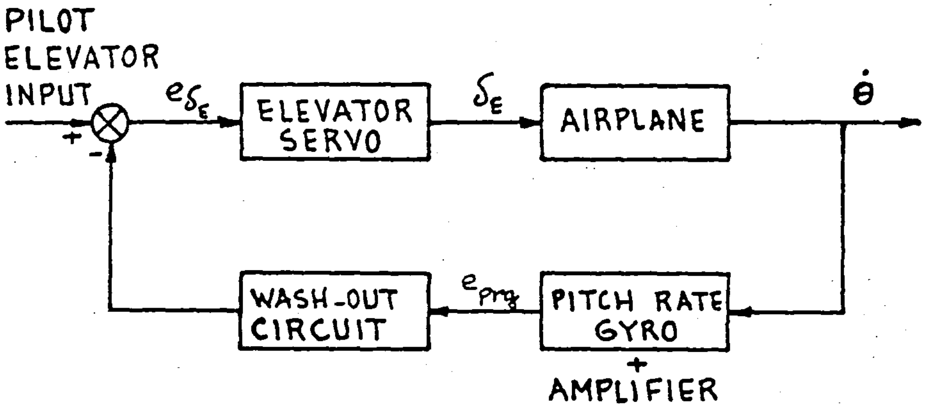


Figure 3.36. - Pitch damper block diagram (Reference 2).

3.4.5 Separate Surface Control

There are some characteristics that make conventional automatic flight controls undesirable. Since most GA aircraft have reversible controls, autopilot-induced control deflections are fed back to the pilot's control wheel. In the case of a hardover failure, the pilot must override the servo directly. Finally, the actuator must move the entire control system with its inertia, friction, and stiction.

These and other reasons have prompted investigation into the use of a surface, separate from the primary controls, that is entirely devoted to the autopilot or a stability augmentation system (see Figure 3.37). Proper sizing of this surface allows the autopilot to have sufficient control power to perform its function yet still leave enough surface for the pilot to retain control in case of a hardover failure. In addition, if full control authority is desired, the separate surface can be slaved to follow the pilot's command. For a list of some of the advantages and disadvantages, see Table 3.8. Much more detailed discussions on separate surface control systems can be found in References 21 through 24.

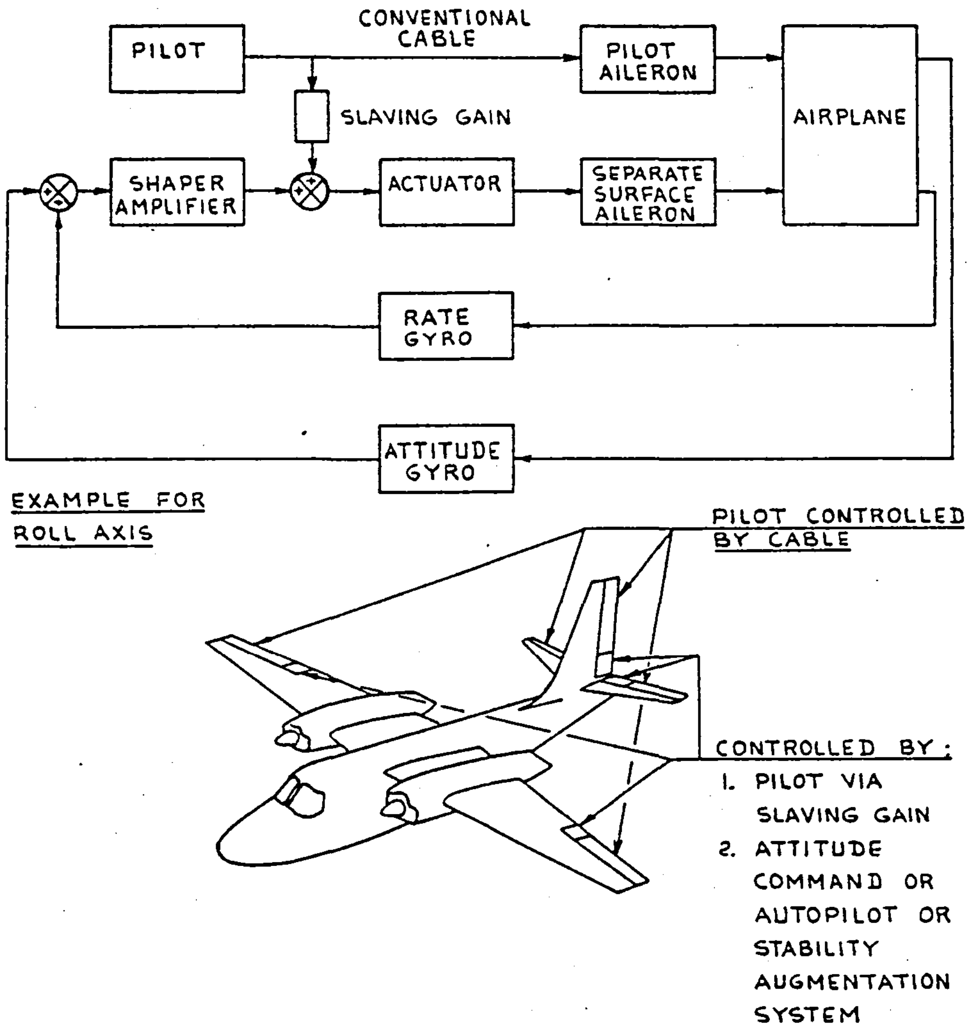


Figure 3.37. - General arrangement of a 3-axis separate surface control system (Reference 23).

TABLE 3.8. ADVANTAGES AND DISADVANTAGES OF SEPARATE SURFACE CONTROL (REFERENCE 2).

ADVANTAGES	DISADVANTAGES
•No Feedback of Stability Augmentation or Autopilot Operation to the Pilot •Full Time Stability Augmentation is Possible •Separate and Combined Auto-pilot or Stability Augmentation Functions are Possible •Response Time of Servo Plus Control Surface is Good •Potentially Lighter Than Conventional System •Pilot-in-the-Loop Operation Possible in All Modes •Full Authority Can Be Given to Separate Surfaces (Hardovers are No Problem)	•No Production or Certification Experience •Cost Not Well Understood

CHAPTER 4

CERTIFICATION AND STANDARDS

Autopilots, per se, do not require certification. It is the <u>effect</u> of the autopilot on the aircraft in which it is installed that is subject to FAA certification requirements. The FAA looks upon the autopilot and the airplane together as a system that must perform safely. In that light, it is the output of the autopilot and the subsequent airplane response that are of primary concern to the FAA.

4.1. TYPE CERTIFICATES (TC's)

For a new airplane to receive a Type Certificate, it must meet a certain set of airworthiness requirements. Most of these requirements are grouped into subsets which correspond and apply to the various subsystems and components of the airplane. If the airplane offers an autopilot as standard, original equipment, a certain group of requirements apply to and must be met by that autopilot if the airplane is to receive a Type Certificate. In this situation, the autopilot is no different than the air conditioner or any other component of the airplane, with respect to certification.

Part 21, subparts B, C, D, and F of the Federal Aviation Regulations (FAR's) define the type certification procedures for all civil, U.S. aircraft. These refer to Part 23 for the specific certification requirements that apply to the subsystems of general aviation aircraft under 12,500 lb gross weight. The applicable section of Part 23, in the case of autopilots, is FAR 23.1329. This section in turn refers to FAA Advisory Circular 23.1329-1A as the document which describes in detail the specific performance criteria which must be met in order for the autopilot to gain approval.

4.2. SUPPLEMENTAL TYPE CERTIFICATES (STC's)

Most autopilots are installed sometime after the original sale of the airplane. The retrofits are done on an indivdual basis. That is, anytime after the original purchase of the aircraft, the owner selects an autopilot that meets his specific needs and has it installed by a certified mechanic. The FAA views an autopilot installation of this sort as a major modification to the airframe, and as such, it must meet FAA requirements. A modification of this kind is not of sufficient proportion to require a new Type Certificate. Once an STC is obtained for a particular autopilot-airplane model combination, it applies to all subsequent combinations of exactly that kind. The autopilot manufacturer usually completes the necessary work to obtain the STC, and lists in his sales literature which airplane models have STC's for his autopilots.

The procedues for obtaining an STC are specified in FAR Part 21, Subpart E. The specific requirements that must be met by the autopilot are again given in FAR 23.1329 and AC 23.1329-1A.

4.3. TECHNICAL STANDARD ORDERS (TSO's)

The FAA has established certain minimum performance and quality control standards that apply to various aircraft components. Any component which complies with these standards qualifies for a Technical Standard Order authorization. It is emphasized that a TSO authorization is not required to produce, sell, install, or operate any Part 23 aircraft component; it is only used to signify that the component meets a set of minimum standards established by the FAA. In that sense, a TSO authorization is analogous to an Underwriter's Laboratories listing on an electrical device. TSO's are required for components of Part 25 (above 12,500 lb maximum takeoff weight) aircraft.

FAR Part 37 addresses the procedures and requirements associated with TSO Authorizations. FAR 37.119 outlines the TSO standard for autopilots and refers to SAE Aeronautical Standard (AS) 402A for the specific requirements. These requirements primarily specify the environmental extremes the autopilot must withstand.

Many autopilots do not have TSO authorizations because either they simply do not qualify or the manufacturer feels that the time and investment required to apply for a TSO authorization outweigh the potential benefits. The latter is often the case with autopilots whose operating environments will be unusually harsh by nature (such as extreme altitudes associated with business jets). Since AS 402A deals primarily with operating standards in environmental extremes, the fact that an autopilot meets these standards may be incidental and, therefore, of little value.

Other publications associated with autopilot certification practices are

1. Special Appendix to Civil Aeronautics Manual 3: Flight Test Report Guide (FAA Form 8110-11)
2. Engineering Flight Test Guide for Small Airplanes (FAA Form 8110.7).

The first of these documents is a guide to aid an applicant for a Type Certificate in making flight tests and in preparing flight test reports. The second details the methods and procedures used by FAA Flight Test personnel to help determine the airworthiness and consequently the eligibility of an airplane for a Type Certificate or STC.

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CHAPTER 5

EVALUATION AND RECOMMENDATIONS

This chapter presents a brief summary of some of the comments made by personnel associated with various organizations in the autopilot industry concerning general aviation autopilot technology. These comments, in conjunction with the documentation of Chapters 3 and 4, form the basis for the conclusions and recommendations also included in this chapter.

5.1 COMMENTS FROM INDUSTRY

5.1.1 Autopilot Manufacturers

Autopilot manufacturers do not conduct any research in the true sense. Rather, their product developers primarily concentrate on applying to their designs the advancements in technology that arise from research conducted elsewhere. These companies typically plan ahead 3 to 5 years.

Sensors and actuators are considered to be the two most unreliable autopilot components. They also tend to be the most costly. Both are due to the fact that sensors and actuators are mechanical in nature.

Fiber-optic signal transmission and laser gyros are looked upon as too expensive at this point to have any application to GA autopilot technology.

Most autopilot manufactuers view separate surface control systems with indifference. The reason is that the only major differences between conventional and separate surface autopilots are some of the component transfer function requirements and the actuator installation. (The actuator is coupled directly to the control surface with separate surface systems.) Further, autopilot companies generally believe there is no significant market for an autopilot or yaw damper that does not feed back to the cockpit controls.

Most autopilot engineers agree that standardization of components and pilot interfaces would decrease cost and improve safety. They believe that component interchangeability would simplify design and installation and thereby cut costs. More importantly, many engineers feel that standardization of controls and displays (pilot interfaces) would make it easier for a pilot to use an autopilot with which he is unfamiliar. The basic appearance of the displays and the operation of the autopilot would be similar to other autopilots he may have previously encountered. Conceivably, accidents caused by pilot error resulting from cockpit unfamiliarity or confusion would be reduced.

5.1.2 Airframe Manufacturers and Service Engineers

In general, airframe manufacturers tend to be cautious with advanced technologies. With autopilots, improvement usually means greater complexity and, therefore, greater risk of failure. Nevertheless, it is believed that the technology exists to make better-quality, more-reliable, and less-expensive autopilot systems and components. Any new technology, however, must be a significant improvement over the state of the art if it is to be considered for application.

It is the general feeling among service engineers that servo mounts (the mechanism which connects the motor to the capstan) should be standardized to simplify and speed installation. Also, it has been observed that servos that house their own fault detect circuitry (instead of it being in the computer) exhibit higher failure rates.

Universal standardization or consolidation of components are viewed as the only measures that could possibly reduce installation costs. Technical improvements would be of little value in this area.

Finally, it was commented that problems with airplane "scalloping" while in VOR hold are often due to small curves and other deviations in the radial beam. In other words, the autopilot is following the signal too well. The obvious solution, which is to reduce the accuracy of the system, can compromise performance in other situations. On autopilots without gain scheduling, this behavior compounds the inherent instability that occurs when nearing the station.

5.1.3 Users

Most pilots would like to see autopilots become less expensive so that more capabilities are available to operators of lighter aircraft. There is no significant demand for new modes. The belief is that many of the capabilities that are available on sophisticated IFCS's could be available on autopilots at the lower end of the market--without great cost.

Single-cue, or V-bar, flight director displays are preferred over cross pointers. Opinions and suggestions concerning the merit and capabilities or autopilots were largely inconsistent.

Pilots are generally unconcerned with autopilot or stability augmentation system feedback to the cockpit controls. With either the autopilot or yaw damper engaged, the pilot conventionally does not touch the affected controls anyway, so little pilot interference exists. Many pilots have found that the control movements aid in monitoring the behavior of the autopilot, much like the flight director. In general, pilots are comfortable with cockpit control feedback.

5.2 RECOMMENDATIONS

Based on the comments outlined above in combination with the documentation presented in Chapters 3 and 4, several recommendations have been developed to air NASA/Langley Research Center in planning any future research in the field of General Aviation autopilots. These are described below.

5.2.1 Application of Laser Gyro and/or Other Strapdown Technology to General Aviation

Strapdown, inertial-type sensors have been shown to have a high MTBF and accuracy. Although the purchase price will always be higher than conventional gyros, life cycle costs will be lower because of greater reliability. Research to determine the applicability of this technology to general aviation would be valuable.

5.2.2 Determination of Safety-Based Design Guidelines for Pilot-Interface Components

Each autopilot manufacturer has its own in-house guidelines on how a safe autopilot should interface with the pilot. These guidelines drive the designer's decisions on such matters as the clarity of a display or the ease of operation of the autopilot. But different manufacturers use different guidelines, which are based on different criteria and studies. This has resulted in a wide variety of controls and displays, some of which may be more confusing or difficult to read or operate than others. A study to determine the proper design guidelines based on certain safety criteria for GA autopilots could be instrumental in reducing aircraft accidents due to pilot error.

5.2.3 Increase in Contact Between NASA and Private Industry

For any research directed toward improving technology in the private sector to be effective, close contact obviously must be established between research personnel and industry. This is especially true in the area of general aviation autopilots. User needs and autopilot technology are both increasing rapidly, and researchers must keep up with these trends to make any valuable contribution. A NASA/industry/university workshop in this area might be very useful.

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CHAPTER 6

REFERENCES, BIBLIOGRAPHY AND RESEARCH PROGRAMS

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