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COMMERCIAL ROTORCRAFT AUTOMATIC CONTROLS—THE NEXT GENERATION

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ABSTRACT

Today's commercial helicopter may now be economically equipped with avionics which give it all the automatic flight capabilities of a modern business jet or commercial airliner. Also, with the addition of full-time stability augmentation equipment and/or careful aerodynamic design, rotorcraft handling qualities approaching those of the airplane have been achieved. The helicopter may now mix with the airplane IFR traffic and land under instrument meteorological conditions (IMC) on an airplane runway, but the unique portion of the helicopter's flight envelope--low speed, hover, and "land anywhere" capability--is still relegated to VFR operations.

At least two factors have been responsible for discouraging low-speed IFR operations: the high pilot physical and mental workload required to maintain stable flight, and inadequate or nonexistent sensors to provide the necessary three-dimensional guidance and motion cues to the pilot. Development programs are now under way which address these deficiencies, and significant improvement in helicopter utilization will become possible in the next few years.

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1. Development History

Until the mid-1970's, only the military and a few large commercial users of helicopters could afford the equipment required for IFR. The need for two pilots, and, therefore, a dual-equipped cockpit, plus overly expensive automatic flight control equipment originally developed for military applications made IFR in the light-to-medium weight helicopter practically beyond reach. Another problem was governmental regulatory agencies who were primarily fixed-wing oriented, and, therefore, reluctant to address the helicopter on its own merits. A cooperative effort was begun in 1974 by Sperry Flight Systems in Phoenix, Arizona and Aerospatiale Helicopter Corporation of Grand Prairie, Texas (then Vought Helicopter Corporation) to attack the problem of economical single-pilot IFR in the light helicopter. This effort resulted in IFR certification of the SA-341G Gazelle in January 1975 - the first unrestricted single-pilot certification to be awarded by the FAA for a production helicopter. Since that time, Sperry, in cooperation with various manufacturers or modification centers, has obtained similar certifications for the Bell 212, MBB BO-105C, Agusta A-109A, Aerospatiale SA-360/365 Dauphin, Bell 222, and Sikorsky S-76. Additional programs are also in process.

2. Typical Helicopter AFCS

Figure 1 shows a block diagram of today's typical automatic flight control system along with additional avionics necessary for IFR operations. Specific installations vary in redundancy levels, axes of automatic control, and optional system features, depending on basic aircraft characteristics, mission, operator preferences, and economy. The flight director system provides a blending of raw situation data into a unified display of computed pilot commands on the attitude director indicator (ADI), while the stabilization system provides aircraft stability as necessary to meet certification requirements. Hands-off automatic path control is obtained by coupling the flight director commands to the stabilization system. Operating modes may be separated into "inner" and "outer" loops for discussion purposes. Inner loop modes selected on the autopilot controller consist of stability augmentation (SAS) and attitude hold (ATT).

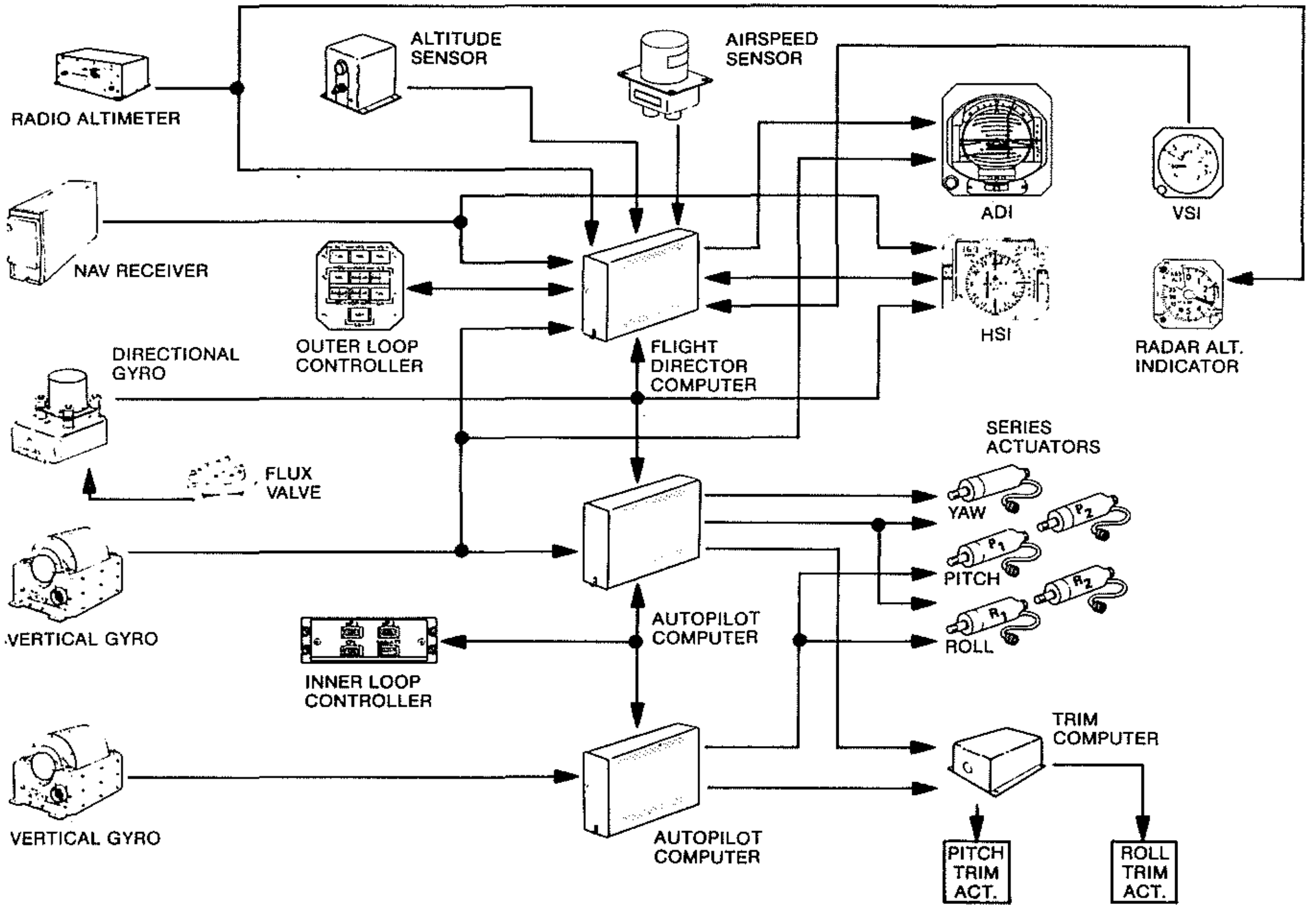

Figure 1
Typical Autopilot/Avionics System

SAS Mode - The SAS mode provides short-term attitude and attitude rate stabilization and is intended for hands-on flight where frequent maneuvering is required (usually VFR). Series actuators in the pitch, roll, and yaw axes respond to aircraft motions and add to or subtract from pilot-applied inputs as necessary to optimize aircraft stability and handling qualities. No long-term commands are applied to the series actuators in the SAS mode, therefore, all required trim changes must be supplied manually.

Attitude Mode - When engaged in ATT, steady-state attitude signals are supplied to the series actuators along with the damping signals, so the aircraft will maintain the trimmed pitch and roll attitude automatically. Automatic parallel cyclic trim is initiated at a predetermined series actuator displacement, thereby allowing the series actuators to continue to operate within their authority limits regardless of control displacement required to maintain the trim attitude. The pilot may maneuver through the cyclic stick in the normal manner, however, attitude will automatically return to the trim value upon release of stick force. Alternately, the pilot may retrim to a new attitude by using the cyclic force trim release switch or four-way beep trim switch. The yaw axis, when included, provides rate damping and turn coordination in all operating modes.

Outer Loop Modes - A wide variety of automatic outer loop (path) modes are available in a modern helicopter AFCS depending on the particular equipment manufacturer and customer options included. The system described herein is typical of that produced by Sperry for several helicopter types. The desired mode is selected on the flight director controller, and the computed commands are automatically coupled to the autopilot whenever attitude hold is engaged.

Modes included are:

Pitch Axis

Barometric Altitude Hold	(ALT)
Vertical Speed Select	(VS)
Airspeed Hold	(IAS)

Roll Axis

Heading Select	(HDG)
Navigation	(NAV)
Back Course Localizer	(BC)
VOR Approach	(VOR APR)

Combined Pitch/Roll Modes

Approach	(ILS)
Go Around	(GA)

When a pitch mode is engaged, the pitch axis of the autopilot is commanded as required (within limits) for capture and track of the selected flight path. Vertical paths (altitude, vertical speed, glide slope) require that sufficient power is manually applied to maintain an airspeed of approximately 60 knots or greater.

A lateral path is captured and tracked by commanding roll attitude. Again, airspeed must be maintained at 60 knots or greater for accurate and coordinated flight path control.

The navigation and approach modes make use of various radio aids depending on the operating environment and user preference. Included may be VOR, VOR/DME Area Navigation (RNAV), Tacan, Omega, VLF, Loran C, Decca, ILS, and MLS.

Operating features include automatic beam capture, selectable intercept angles, crosswind compensation, beam convergence compensation, complementary noise filtering, and so forth.

3. System Limitations

As can be seen from the above operational description, the AFCS applies primarily to the cruise portion of the flight envelope. This is particularly true for the outer loop modes. There are valid reasons why this situation exists. The autopilot and flight director systems in use can trace their origins to adaptation of equipment designed for fixed-wing applications. Principal differences which have evolved are associated with basic aircraft design characteristics (boosted vs. unboosted controls, for example), rather than differences in operating environment. There has been little incentive to emphasize low-speed flight since the helicopter has been forced into the airplane traffic system and is expected to maintain airplane speeds and approach patterns. In cases where an operating environment has been established specifically for the helicopter, such as that to offshore drilling rigs or helipads at remote construction sites, then the limitations of present systems become apparent. Accurate navigational guidance to the destination is required at low altitudes where line-of-sight coverage from a land-based navigation aid is not sufficient. As the landing pad is approached, it is necessary to decelerate from cruise to near hover, while at the same time descending to the minimum allowable IMC altitude. Conventional airspeed sensing systems become useless, therefore, an alternate means to provide velocity data is required. Three-dimensional path stabilization, in addition to three-axis attitude stabilization, should be supplied due to the strong cross-axis coupling present in this flight region. For example, power changes necessary to maintain altitude or vertical velocity affect attitude and heading, and attitude changes necessary to maintain the flight path and velocity in turn affect the power required. It has been repeatedly demonstrated that a pilot rapidly becomes saturated in workload when attempting to maintain a stable flight path in this speed region, even when attitude stabilization and manual flight director commands are provided.

4. New Development Activities

Fortunately, research programs over the years, primarily for organizations such as NASA or various military agencies, have been addressing the problems of low-speed path control, and solutions have been available, waiting for a need to materialize. Sperry is now actively engaged in applying these solutions, which is resulting in development of system modifications and additions as well as completely new systems which should make IFR flight in the zero to 50 knot speed region routine. Some of the more significant additions are described below.

Three-Cue Flight Directors

One of the first steps toward expanding the IFR flight envelope of the helicopter is to provide complete command guidance data for use by the pilot. Early in the history of adaptation of fixed-wing flight director equipment to helicopters, the need for power management was recognized, particularly during approach and climbout. By the late 1960's, the concepts for three-cue computation were well established. Sperry's first production flight director for helicopters provided full collective command capabilities; however, for the reasons previously discussed, it saw little use in normal IFR operations. The requirement is developing again with the introduction of microwave landing aids which permit cockpit selection of steep path, low-speed approaches. The third-generation flight director system currently under development by Sperry not only supplies power commands for display on the ADI, but also provides servo commands to a collective pitch autopilot axis, thereby permitting fully automatic control of the vertical axis throughout the flight envelope.

Operation in a three-cue mode is similar to that described in (2) above, except that any vertical mode (altitude, vertical speed, glide slope) may be flown simultaneously with airspeed hold. When airspeed and any vertical mode are engaged simultaneously, the pitch axis is controlled by airspeed error and the collective axis is controlled by the appropriate vertical path error. When flying in this manner, it is no longer necessary to stay on the "front side" of the power curve, as is the case for two-cue operation. Note that, even with this added capability, speeds below approximately 40 knots are still not practical because reliable airspeed data is not usually available.

Inertial Velocity Stabilization

Another system concept developed in the 1960's provides a solution for the lack of reliable low airspeed data, and also helps maintain stable lateral path guidance at speeds where heading error no longer approximates lateral deviation rate. Longitudinal and lateral accelerometers are gravity-stabilized by a vertical gyroscope and the outputs are electronically integrated to generate short-term inertial velocities along the longitudinal and lateral axes of the helicopter. When these velocity signals are added to the pitch and roll axes of the SAS, the aircraft becomes very stable translationally, resistant to external disturbances such as wind gusts. With the addition of synchronizing circuits and command augmentation, any lateral or longitudinal velocity may be easily established through normal maneuvering, and is then automatically maintained within the precision inherent in the sensors and electronics employed. Hands-off drift rates of 5 knots per minute or less have been obtained.

Although the velocity stabilization system was originally designed as an aid in hands-on hover, it has been found to be effective as an inner loop damper for outer loop path guidance systems, over the speed range from hover to 60 knots. Figure 2 shows a block diagram of the inertial velocity control system interfaced with a microwave landing system (MLS). Operation in the approach mode is as follows. Lateral path errors are summed with lateral inertial velocity to command the roll axis of the autopilot. The desired longitudinal velocity, computed as a function of distance to touchdown, is summed with longitudinal inertial velocity to command the pitch axis, thereby achieving stable hover at a specified distance from the MLS transmitter. Vertical errors (glide slope) are supplied to the collective axis, where short-term velocity damping is provided from vertical acceleration signals complementary-filtered with barometric altitude rate data. To complete the low-speed automatic approach/hover system, the yaw axis of the SAS must be modified to provide more than yaw rate damping.

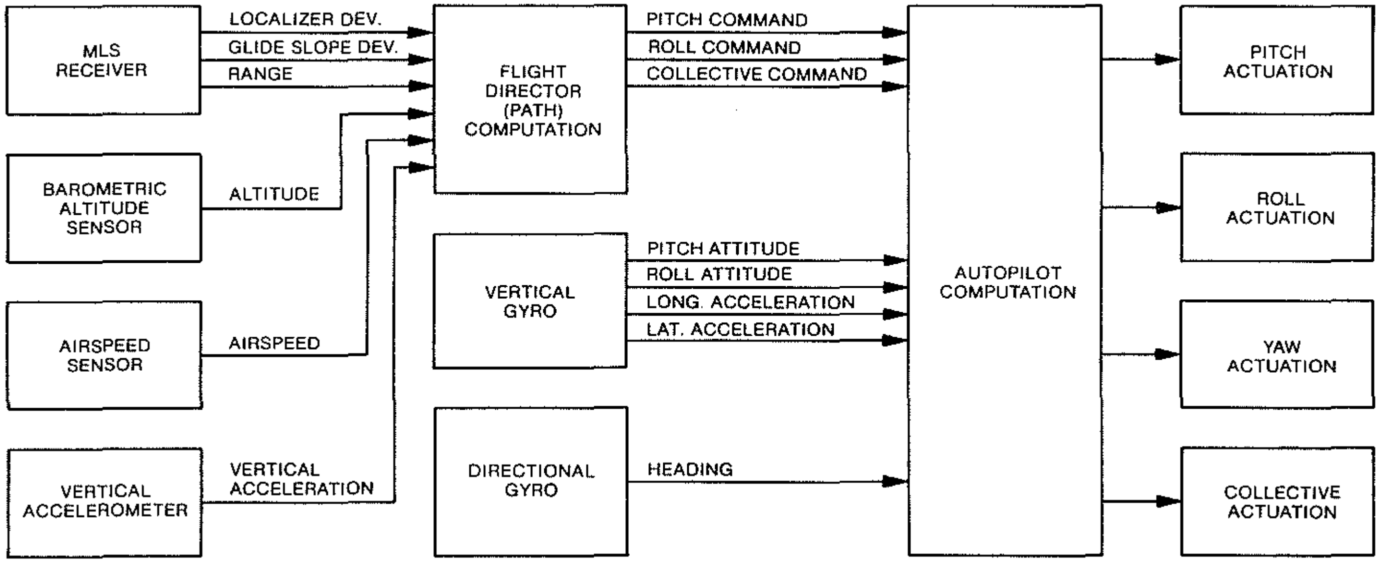

Figure 2
Coupled Steep Approach
System Block Diagram

Heading Stabilization Through Yaw

When attempting to maintain a hover or a stable low-speed flight path, it is necessary to keep the aircraft heading fixed or aligned along the desired flight path. Heading is normally controlled in cruise flight through the roll axis, as described in (2) above, while pedal control is used only for Dutch roll damping and turn coordination. However, heading control must be transferred to pedals as speed is reduced. At approximately 60 knots, the control laws are automatically modified. Heading error is supplied to the yaw series actuator along with yaw rate to provide the small amplitude, high-frequency corrections, and long-term pedal trim is provided by a parallel trim actuator. Desired heading changes are commanded by the pilot by normal maneuvering through the pedals or by operating a heading "beep" switch.

Special-Purpose Operational Modes

As the above-described features are added to the helicopter AFCS, other operational capabilities are made possible. In particular, an approach-to-hover mode is currently under development for use primarily in over water search and rescue missions. This mode makes use of the inertial velocity stabilization system previously described and adds a radar altitude hold function operating through the automatic collective pitch control axis.

The system permits full hands-off transition of the helicopter from a cruise condition to a hover (or predetermined airspeed near hover) and controlled descent to a preselected radar altitude. No externally referenced navigation or approach aids are required for this mode. The approach-to-hover mode is performed in two stages, as shown in the diagram of Figure 3. The approach is initiated by selecting the desired hover altitude (0 to 1000 feet) and engaging the first stage (APP 1). The aircraft begins a constant deceleration of 0.05 to 0.1 g, depending on operational requirements, and a descent of 600 feet per minute. The descent will terminate at the selected altitude or 100 feet, whichever is higher, and the deceleration will terminate when the longitudinal speed reaches the preset minimum which may be based on wind conditions or other operational considerations. Since actual airspeed below 40 knots cannot be accurately determined, a prediction is performed based on last valid data and sensed acceleration. When the second stage of the approach is engaged, the descent continues to the selected reference (as low as zero feet AGL). Descent rate is reduced to 300 feet per minute in this stage. At any time during the approach or after reaching a stable

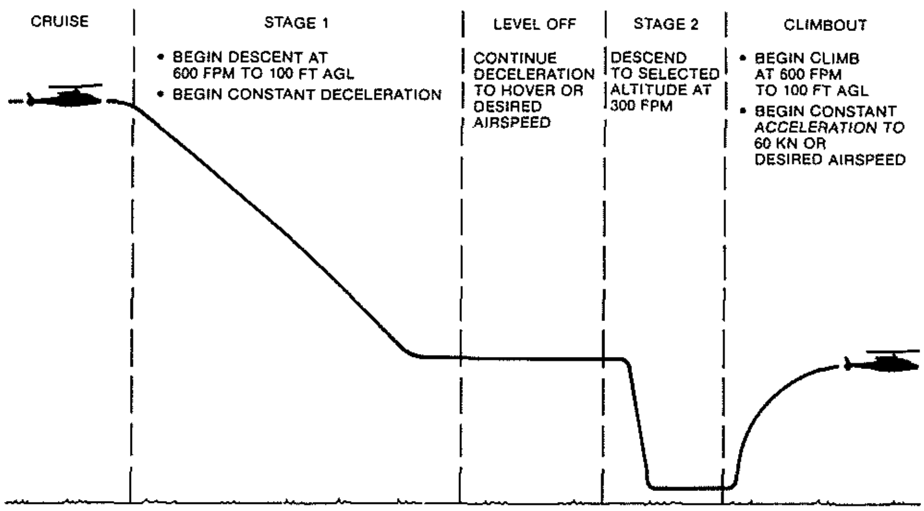

Figure 3
Automatic Approach-to-Hover/Climbout
Flight Profile

hover, an automatic climbout mode may be engaged. This mode commands a constant acceleration and climb rate to a safe altitude and airspeed, typically 100 feet and 60 knots, although any other values can be specified. Figure 4 shows a time history of an approach and climbout performed with flight hardware interfaced to an analog computer representation of the helicopter. The approach was initiated with the aircraft in a climb, and airspeed approximately 60 knots. The deceleration and acceleration level was set at approximately 0.1 g, and terminal altitude was set at 15 feet AGL. Sensor inaccuracies were included in the simulation, and a drift in airspeed may be observed after the climbout is completed, due to electronic null errors and precession of the vertical gyro from true vertical during the acceleration. A trimmed condition of zero acceleration (constant velocity) is easily reestablished by operating the cyclic fore-aft beep switch. A normal operating procedure following the climbout would be to engage airspeed hold, in which case the proper cyclic trim for constant speed would be automatically established.

Other applications of the approach-to-hover feature may be envisioned. One which is immediately obvious is to use the system as an aid in a weather radar approach to an offshore drilling platform. Here, guidance data (range and azimuth) to the landing site is observed by the pilot on the radar display, and the approach mode is engaged at a distance appropriate to the desired deceleration level. The terminal radar altitude and airspeed would be selected

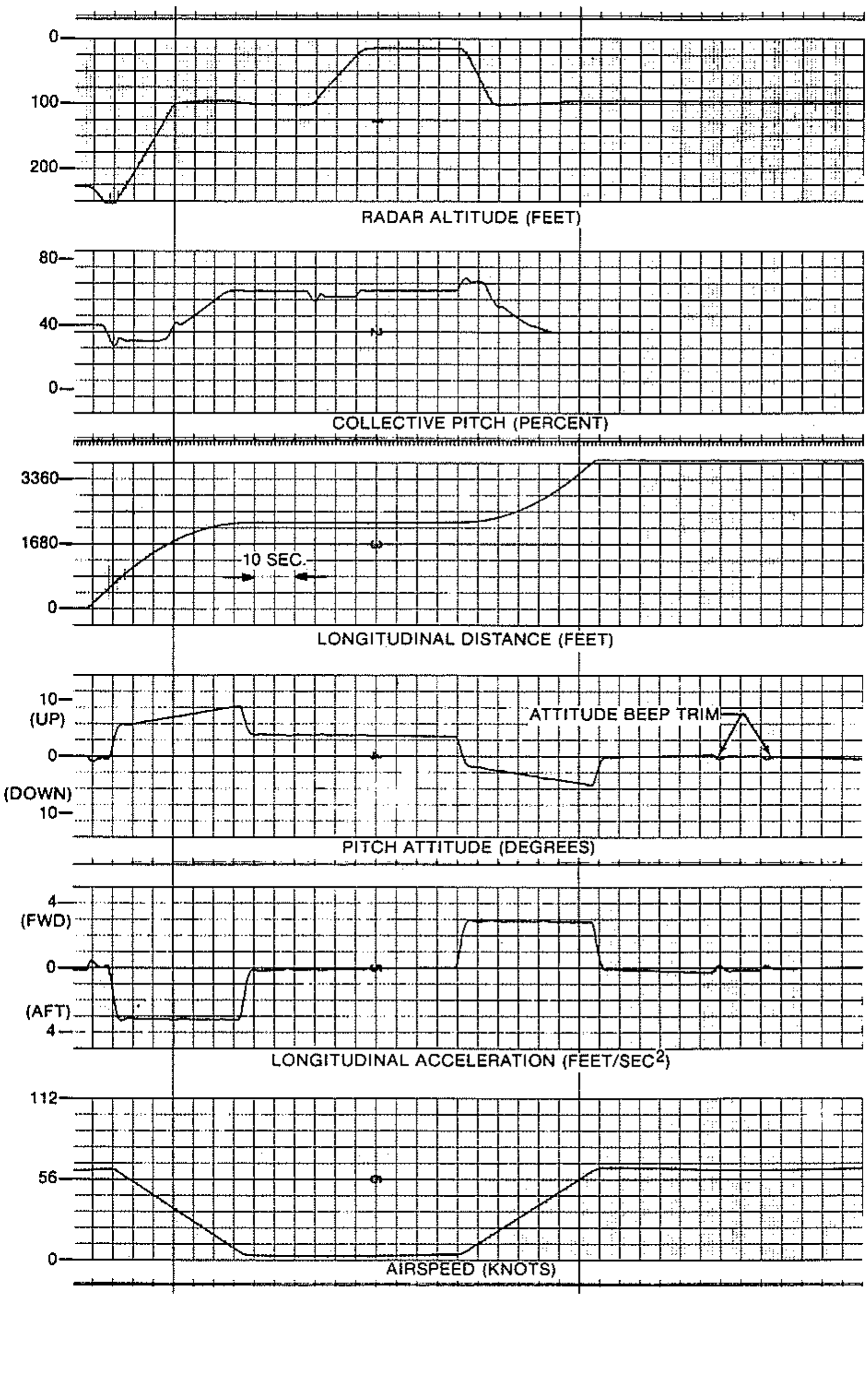

Figure 4
Approach Time History

to coincide with the approved minimums. During descent and deceleration, the pilot's workload associated with control of the aircraft will be relieved such that he may monitor the progress of the approach both from inside and outside the cockpit. In the event that breakout has not occurred at minimums, the climbout feature may be used for go around to establish sufficient airspeed for the normal go-around mode.

5. Conclusions

In only 5 years, the autopilot has gained wide acceptance in the light-to-medium weight helicopter. In addition to enhancing utilization and operational safety, it has played a key roll in establishing the helicopter's legitimacy in the civil IFR environment. We are now looking at ways in which automatic flight controls might further expand the usable flight envelope of the helicopter, permitting completion of missions under instrument conditions which are now limited to VFR. The added system capabilities and features described herein will be the first toward that end, and will, hopefully, encourage accelerated deployment of approach aids and heliports to specifically serve the rotary-wing community.