DESIGN FEATURES AND TEST RESULTS OF AN UNMANNED FREE SWIMMING SUBMERSIBLE

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ABSTRACT

Presently various underwater tasks are accomplished by means of tethered platforms or manned submersibles. Due to the high costs of men and ships the Naval Research Laboratory (NRL) is developing an Unmanned Free Swimming Submersible (UFSS) to demonstrate that an autonomous vehicle may be used as an alternate method to undertake these tasks. This paper discusses the design features of this vehicle and the results of recent shallow water tests in the Patuxent River. These tests proved that UFSS could maneuver autonomously using its microcomputer. The tests also proved that under certain environmental conditions the vehicle could adapt to these conditions by use of the microcomputer and associated real-time software.

INTRODUCTION

The rapid increase in ship and personnel costs which has occurred in executing certain Navy functions and missions has suggested that certain innovative approaches may be fruitful in reducing costs when these approaches are compared to conventional means of accomplishing these tasks. As an example, the Naval Research Laboratory (NRL) has employed a towed "fish" for many years to obtain oceanographic data and to search for sunken submarines such as the THRESHER. Unfortunately the cable drag only permits speeds of approximately 1 knot. Accordingly, under the sponsorship of NAVSEA, NRL is developing an Unmanned Free Swimming Submersible (UFSS) to demonstrate the concept of an alternate capability to perform these tasks.

The UFSS vehicle is 20 ft long, 4 ft in diameter and 125 cubic ft in volume. It employs a low drag hull so that a substantial endurance may be obtained with a relatively inexpensive energy source (lead acid batteries). The vehicle incorporates a pressure vessel (75 cubic ft in volume) which remains at atmospheric pressure and houses most of the electronics and a battery. The rest of the vehicle is flooded (50 cubic ft). The maximum intended operating depth is 1500 ft. Crush depth of the internal pressure vessel is 3000 ft. The low drag portion of the hull is made of fiber glass and measures about 70% of the entire length. The after portion of the hull is made of aluminum. Figure 1 is a photograph of the vehicle. UFSS is an autonomous vehicle and is being designed to obtain OMEGA fixes while submerged. Real-time software, imbedded in a microcomputer, provides the vehicle with an autonomous guidance and control capability. The vehicle incorporates a variable ballast system to vary the vehicle ballast as required by environmental and operational conditions. A flux gate compass together with other vehicle sensors (including attitude sensors) are integrated into the system. Although the hull is designed for laminar flow at relatively low speeds (5 knots), UFSS has several advantages over high speed laminar flow vehicles namely: 1) Smoothness requirements are not demanding and operational damage may be easily repaired aboard ship. 2) A large vehicle is feasible. 3) Energy is conserved thus permitting a high endurance operation. An acoustic telemetry system employing a microcomputer has been incorporated as a backup system to give UFSS over-ride commands and also to receive test data at a surface vessel.

The initial testing was completed in the Patuxent River at Solomons, Maryland (near Chesapeake Bay). These shallow water tests verified that the vehicle functioned autonomously. Prior to a test an umbilical cable was employed to give UFSS guidance commands. The umbilical cable was then withdrawn and an acoustic "enable" command was issued from a surface craft to cause UFSS to commence its test. It was proved that the vehicle could dive, turn, maneuver autonomously, and under certain conditions adapt to environmental conditions. The tests also confirmed that a low-drag body may be launched, retrieved, and towed effectively. Since the Patuxent River was quite shallow and the test area was relatively confined, neither the acoustic telemetry nor the OMEGA navigation systems could be tested. Likewise the hull could not be tested for laminar flow because of water turbulence; however, recent model tests confirm the theoretical calculations that the drag is approximately one-third that of a conventional hull over most of the velocity range considered. Deep water tests are needed to prove out the acoustic telemetry, OMEGA navigation system, and the low drag nature of the hull.

DESIGN FEATURES

The various subsystems that constitute the UFSS system are shown in Fig. 2. The guidance and control (GC) computer is intimately associated with most subsystems and either controls their operations or performs many of their functions. The topside subsystem and failsafe subsystem are essentially independent of the GC computer but even here these subsystems interact with the computer for certain functions. The following describes the design features of significant subsystems.

HULL

The UFSS vehicle was designed at NRL using hydrodynamic optimization techniques to minimize drag but still consider practical matters such as packaging, launching, and handling. The design results in a submersible with a drag which is approximately one-third that of a conventional vehicle. The design methodology first makes use of the Parsons-Goodson numerical routine (1) to obtain an optimum profile and yet satisfy non-hydrodynamic constraints such as packaging considerations. By use of this routine with added refinements a profile was chosen by iterative techniques which ensured the requirement that transition did not precede laminar separation.

The hull was designed for a volume of 125 ft^3 at a speed of 5 knots in water at a temperature of 40^oF. The design incorporated a safety factor so that the hull would remain in a laminar mode at either a somewhat higher temperature or speed. NRL experiments with an UFSS hull model in the U.S. Naval Academy tow tank confirm the theoretical calculations that the drag is one-third that of a conventionally designed hull at the speeds of interest (2).

The hull was also designed to accommodate certain practical matters. Eyebolts may be inserted at the stagnation point on the nose and also at two points in the aluminum tail section (aft of laminar separation). When not being used for towing or handling, the eyebolts are removed and the holes are capped off. Because the vehicle operates at low speeds, the tolerance on surface roughness is not very demanding. Thus any dents from handling and operations can be repaired aboard ship. A high speed vehicle must be highly polished to operate under laminar conditions. Another practical consideration is the fact that a vehicle should be large enough to carry a substantial payload as well as its own electronics, energy source and mechanical accessories. A large vehicle such as UFSS can be designed when speeds are relatively low. A large high speed vehicle, on the other hand, is not physically realizable based on optimization techniques using shape alone.

MANEUVERING SUBSYSTEM

The control system for UFSS was developed by using the conventional set of 6 degree-of-freedom equations of motion for the submersible vehicle dynamics (ref. 3) and then decoupling the lateral and longitudinal transfer functions. Coefficients of these transfer functions are functions of hydrodynamic coefficients which were estimated (ref. 4). By use of linear control system analysis and synthesis techniques using the S-plane and root locus plots the control system was designed. The controller was then implemented in the GC computer using an update rate of once a second. The design was refined with the aid of a 6 degree-of-freedom digital simulation where the UFSS maneuvering capability was tested prior to sea tests. The update iteration rate of once a second was quite adequate.

A block diagram of the depth control configuration in analog form is shown in Fig. 3. It consists of an outer depth to elevator feedback loop for depth control and an inner pitch plus pitch rate loop for pitch control and improved stability. Integral compensation is employed in order to reduce depth error to zero for a non-neutrally buoyant vehicle. The integral compensator automatically computes the required negative pitch trim command for level flight with a net positively buoyant vehicle. Logic has been included to engage the input to the integrator only if the depth error is less than 25 ft in order to reduce depth overshoot. The heading controller is rather simple and includes an outer heading to rudder feedback loop with an inner yaw rate feedback loop for augmented damping. Reference 5 describes the UFSS control system in detail.

NAVIGATION

The UFSS vehicle is designed to navigate by OMEGA while submerged at shallow depths and by a flux gate compass and speed sensor at depths greater than 50 ft. In normal operation UFSS would obtain an OMEGA fix at shallow depths and then dive to reasonably deep depths where it would dead reckon its position with the aid of the flux gate compass, the speed sensor and the GC computer. Periodically UFSS would ascend to obtain a new OMEGA fix.

OMEGA is a worldwide navigation system consisting of eight transmitting stations positioned around the world. Position is determined by the solution of hyperbolic lines of position using three VLF frequencies transmitted by each station. The OMEGA receiver on UFSS tracks all three frequencies from all eight OMEGA stations and chooses the best signal for fixes. Calculations indicate that the OMEGA system employed can obtain fixes at a depth of 50 ft. The system has the ability to resynchronize and obtain fixes while submerged at shallow depth after UFSS dives and later ascends from a deep depth.

Since OMEGA operates on phase information, ambiguity results when UFSS transits from one lane to the next. The unambiguous lane width for a three-frequency OMEGA system is about 70 miles. Since UFSS has a range capability of 100-125 miles using lead-acid batteries, OMEGA operation in UFSS for 100 miles will prove that a submersible may navigate from one unambiguous lane to the next for unlimited distances for navigation purposes. With exotic energy devices such as lithium thionyl chloride batteries UFSS has a potential endurance of 200 hours and can navigate using OMEGA through several lanes as UFSS cruises at deep depth and periodically ascends to obtain a submerged OMEGA fix.

PROPULSION

This subsystem includes a one-half hp 3-phase induction motor, a motor controller and a propeller with a pitch of 22 inches. Since the ac motor is flooded with oil and hence pressure compensated, reliability is much better than motors that are not flooded and require dynamic seals. Furthermore, the ac induction motor eliminates the need for brushes and associated high maintenance which are required by dc motors.

The motor controller operates off the 110 V dc battery bank and converts the dc to 3-phase ac which is pulse width modulated. The GC computer specifies speed by sending an appropriate signal to the motor controller which converts the dc battery voltage to a variable frequency of 5 Hz to 51 Hz depending on speed requirements. A constant volts/hertz ratio is maintained by varying the pulse width modulation as speed changes. The motor controller also incorporates certain failsafe functions. For example, if the propeller is fouled by a line, a tachometer signal is fed back to the controller and sensed by a locked rotor detector circuit which causes a reduction of motor slip to a value which is adequate to prevent overheating.

TRIM AND VARIABLE BALLAST

The vehicle incorporates a trim and variable ballast subsystem to vary the vehicle pitch angle as well as the net buoyancy. Changes in trim and ballast may be made by means of instructions via the umbilical cable. Alternately, the ballast may be changed by means of preprogrammed instructions from the GC computer.

Trim is changed by pumping hydraulic oil which in turn shifts mercury between two fore and aft tanks within the pressure vessel. Buoyancy is changed by pumping hydraulic oil between a flexible reservoir inside the pressure vessel and another flexible reservoir outside the pressure vessel. Buoyancy is decreased by pumping oil into the reservoir inside the pressure vessel.

COMMAND AND DATA ACQUISITION

This subsystem consists of two modules which are controlled by a common microcomputer. One module is a tape recorder which permits selected functions to be recorded. The other module consists of an acoustic telemetry unit. The microcomputer permits excellent flexibility in the selection of parameters and sampling rates.

The acoustic telemetry module consists of a data link and a command link using differential phase shift keying at a carrier frequency of 40 kHz. The telemetry is a backup for UFSS which would normally operate in an autonomous mode. A support vessel would tow a "fish" with "topside" telemetry which would communicate with UFSS telemetry over a large area shaped like an annulus in the horizontal plane. The maximum and minimum radii of the annulus surrounding the "fish" are parameters which optimize the telemetry for multipath considerations. The maximum distance is the point at which the difference between the direct path and the reflected path is 8.5 ms (3 ms for a 12 bit word transmitted as a burst and a 5.5 ms safety interval). The minimum distance is the point where the third reflected path (between bottom and surface) is 0.5 seconds. This point is chosen since a data burst is transmitted every 0.5 seconds and any reflections greater than 3 are attenuated below the sensitivity of the receiver.

The acoustic command link (down link) employs an error correcting code. If an error occurs UFSS corrects it and returns the signal to the support ship where the operator verfies it and transmits an execute command at which time the over-ride command is carried out. Data signals (up link) are used aboard the support vessel to observe the performance of various UFSS parameters.

FAILSAFE

This subsystem is designed to operate independently from the GC computer with the exception of a few functions which may be programmed prior to a test. The following are some of the functions that are monitored. Leaks are checked in the pressure vessel to cause either an alert or an abort depending on the amount of water detected. Periodic pulses from the GC computer are checked; loss of pulses indicates that a failure has occurred. If certain thresholds are out of tolerance for critical voltages or temperatures, the failsafe logic will cause certain responses to occur. Likewise, if a specified depth is exceeded or the mission time is exceeded an appropriate action will occur. The failsafe monitors periodic signals from the Digital Acoustic Command System (DACS) on the support ship to ensure it has not lost contact. Finally an external abort signal from the DACS is monitored.

Depending on the nature of a failure the failsafe equipment will cause certain commands to occur. It may also record the failure in the recorder module or alert the topside equipment by telemetry. An abort command causes UFSS to release 150 pounds of weights and to surface. The abort may be generated internally, or externally by DACS. The initiation of an alert causes the GC computer and telemetry to be signaled. A surface command causes UFSS to surface. A circle command will cause UFSS to turn in a circle for a period of time until it later is commanded to surface. Lastly, the actuation of a pinger command requires a transponder on UFSS to ping periodically at a certain rate to facilitate finding UFSS.

GUIDANCE AND CONTROL (GC) COMPUTER

This computer employs an 8080 microprocessor and card modules of the Intel Single Board Computer series. Six cards are employed for this microcomputer which consists of 24K of erasable programmable read-only memory (EPROM), 5K of read/write volatile memory (RAM), a 16 channel multiplexed analog to digital converter, an 8 channel digital to analog converter, and a crystal controlled real-time clock to interrupt the microprocessor every second. The computer has 12 ports each of which has 8 parallel input/output lines to communicate with various subsystems. Additionally, the computer has a serial teletype interface and a serial input/output channel with an RS232 interface.

GC COMPUTER SOFTWARE

NRL developed most of its software by use of PLM, a compiler language. A few routines were written in assembly language. The PLM software was compiled in a PDP10 computer and verified in an Intel Microcomputer Development System (Intel MDS-800). This MDS system was used to interface with other subsystems to check out software and integrate the UFSS system. After software was verified EPROM memory, which can be erased by ultraviolet light, was programmed by the MDS equipment and packaged into the GC computer.

The GC computer operates in either the monitor mode or the real-time mode. When power is first applied to the GC computer, it is forced into the monitor mode at which time it is programmed by means of a teletype and an umbilical cable. After programming the GC computer, the operator typically checks out the UFSS system by switching to the real-time mode to checkout various subsystems and print out selected data. He can also exercise control surfaces by employing a step and deflect routine whereby the surfaces periodically transit maximum deflections in each direction in 3-degree increments.

When UFSS has been checked out and programmed, operation is transferred to the real-time mode whereby the executive schedules tasks on a time and priority basis. Once a second control is transferred from the current task to the executive by the real-time interrupt and a new task is assigned based on priority and schedule. Guidance instructions will not be initiated until an acoustic enable signal is received from a Digital Acoustic Command System (DACS) on the support ship. When this enable signal is received, a flag is set in a specific memory location. When the executive program schedules the guidance subprogram the flag is checked. If in fact the flag is set, guidance instructions will be carried out.

TOPSIDE

Topside equipment consists of an AMF 301 tracking system, an AMF 701 DACS, acoustic telemetry, a teletype, and an HP 21MX computer and associated peripheral equipment. Only the teletype, the tracking system and the DACS were used during shallow water testing on the 45 ft utility support boat. The HP 21MX was used ashore to analyze data from the recorder module.

New guidance programs were given to UFSS by means of the teletype and umbilical cable. After receiving an acoustic enable from the DACS, UFSS proceeded to carry out guidance instructions while being tracked. Pings sent out by DACS caused UFSS to transpond with a ping which was used by the 301/701 system to obtain range and bearing. The 701 system could send signals to UFSS to abort a test, cause an emergency surface, or cause the previous test to be rerun without reprogramming.

TEST RESULTS

After the system was integrated, the vehicle was tested in a tank at NRL. Salt was added to the water in the tank to match the salinity at the mouth of the Patuxent River. Ballast was added to UFSS to set the static pitch equal to zero degrees and the overall buoyancy at 30 lbs positive.

Shallow water tests were completed between July-September 1979 near the Chesapeake Bay at the mouth of the Patuxent River. The Naval Surface Weapons Center (NSWC) Facility, Solomons, Maryland was used as a base for the operations. Prior to arrival at NSWC a detailed test plan had been developed. In order to facilitate the implementation of the test plan the NRL team implanted four buoys at stategic points in the Patuxent River to form a test range. The buoys were used for the three-month test period; their geodetic positions were measured accurately and checked during each test by means of sextants to measure horizontal angles of fixed points ashore and a three-arm protractor to plot the buoy positions.

Tests normally started early in the morning and were completed late in the day. UFSS was launched from the NSWC craneway and towed by a 45 ft utility boat to the test range where a rubber boat was used to service UFSS. At this point eyebolts were removed, holes were capped off and buoyancy was checked. If buoyancy was out of tolerance, weight would be added or subtracted by fixed weights attached to cover plates in the tail. Additionally, ballast could be varied by exercising the variable ballast subsystem using commands from the teletype via umbilical cable . After guidance instructions were issued to UFSS, the umbilical cable was removed, the rubber boat was returned to the utility boat and an acoustic enable command was issued from the DACS. UFSS then proceeded to carry out its orders.

A few problems were encountered early in the test program such as intermittent operation from a cold solder joint and a connector. The software functioned exceptionally well even in the initial tests; however, one or two minor changes were made to improve the operation. After these problems were corrected,UFSS demonstrated its capability to operate autonomously and perform various maneuvers such as multiple depth dives, open and closed loop turns, and zig-zags. Near the end of the test period as many as four tests per day were completed.

A few unexpected difficulties occurred which were readily solved. One of these problems was the fact that when wave action occurred with a wavelength approximately equal to the length of UFSS, the vehicle encountered more buoyancy at the surface than it did while submerged. This problem was compounded when UFSS experienced strong winds and a state 2 sea. When these conditions occurred,it was difficult for UFSS to dive with a prudent amount of positive buoyancy. The weathercocking effect of strong winds was solved by requiring UFSS to head into the wind while on the surface and to alter course after it had submerged. The other problems were solved by making UFSS adaptive. To overcome the surface buoyancy effect the depth/pitch controller was required to generate more gain at the surface. Gain was relaxed to normal when UFSS reached a depth of 10 feet. To overcome the seaway problem the variable ballast was exercised operationally to "bootstrap" a dive. Logic in the software was changed with the following subprogram as a "bootstrap" option. If a dive was commanded and UFSS failed to exceed a depth of 10 ft in 1 minute, ballast would be pumped into the pressure vessel until UFSS reached a depth of 10 ft or 10 lbs of buoyancy was pumped. When one of these conditions was reached the GC computer caused the variable ballast subsystem to pump out the amount of ballast which was previously pumped into the pressure vessel. The combination of these solutions proved very effective in overcoming these surface environmental problems.

Figure 4 depicts a typical test result, a multiple depth dive. UFSS was instructed to dive at 15 ft for a period of time, then to 25 ft, back again to 15 ft and finally to surface. Because of shoal water constraints, the run could continue for only 960 seconds. A slight amount of overshoot occurred for the reasons previously explained. Due to the short run times UFSS never completely settled out at each depth. Figure 5 shows the result of a 180° change of course at 15 ft. depth. Near the surface UFSS was commanded to head into the wind (approximately 300° magnetic);at 15 ft depth course was altered to 260° magnetic. After a period of time UFSS was required to reverse course to 080° magnetic.

CONCLUDING REMARKS

On a separate project NRL is developing advanced control techniques for Naval vehicles. Specific goals include the innovation of: 1) robust control systems that are insensitive to changes in vehicle dynamics and the environment, 2) adaptive control systems that can identify changes in system dynamics and compensate automatically by reconfiguration, and 3) computationally efficient control algorithms which can be implemented in real-time in microcomputers.

The NRL approach to this project is to complete it in two phases. During the first phase system parameters (including hydrodynamic coefficients) are identified off-line using an extended Kalman filter. Good progress is being made on this phase. UFSS was used as a test bed for this phase and certain information was identified off-line using data from the shallow water tests. Additionally, the technique was tested by computer simulation using known information and using the extended Kalman filter to estimate parameters off-line. During the second phase parameters will be identified on-line and an optimal controller with adaptation logic will be used to obtain optimal gains. This second phase has commenced and a reduced state adaptive Kalman filter has been formulated with a covariance factorization algorithm that optimizes computational efficiency.

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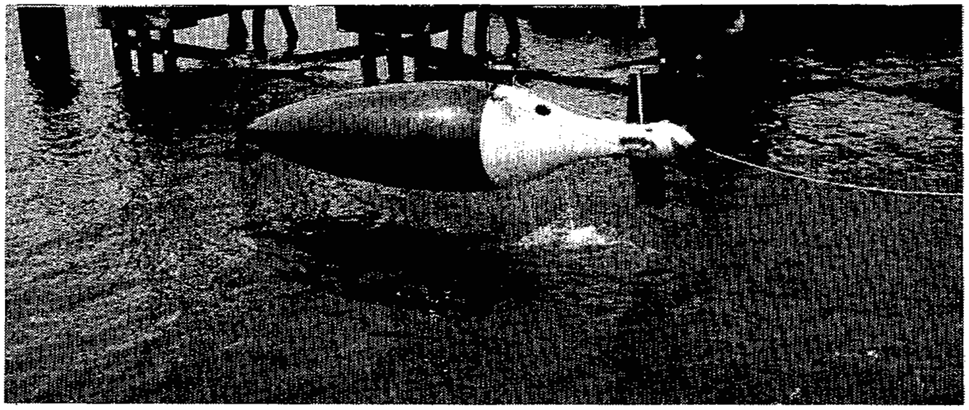

Fig. 1 UFSS

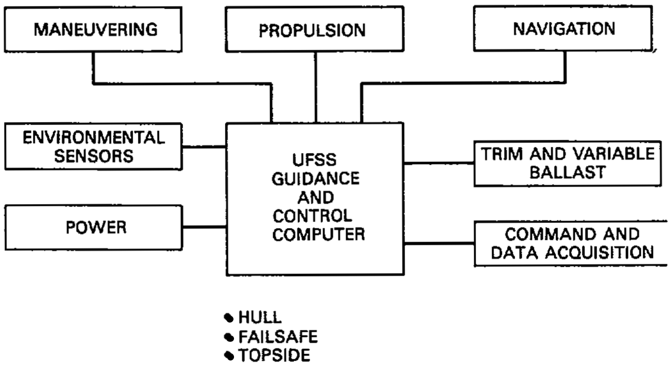

Fig. 2 System Configuration

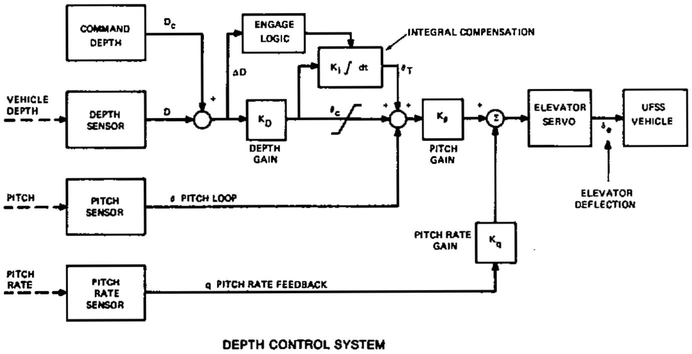

Fig. 3 Depth Control System

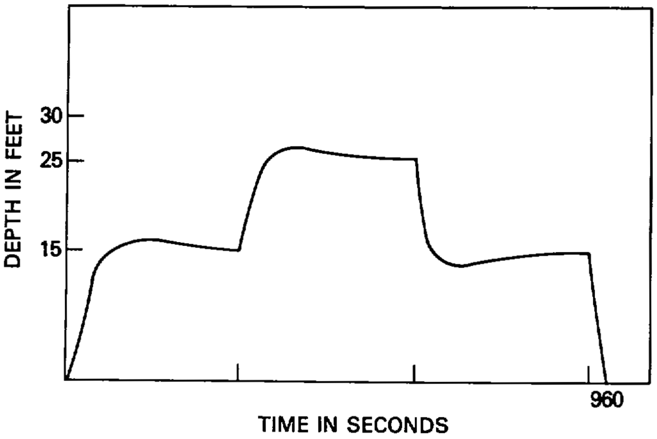

Fig. 4 Multiple Depth Dive

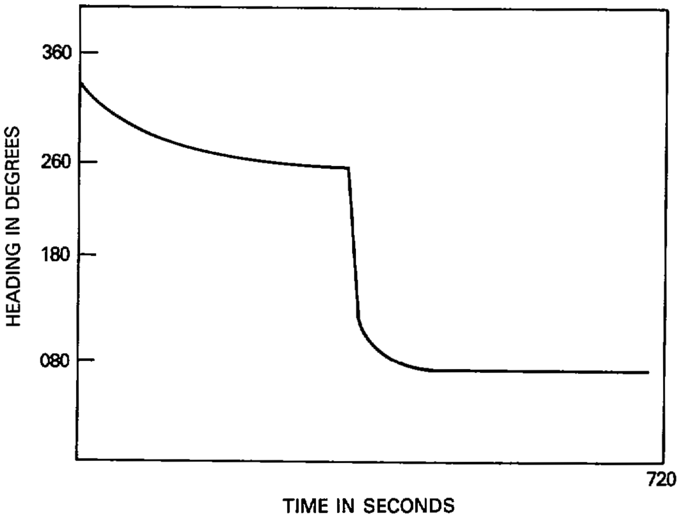

Fig. 5 180° Course Change