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Automatic Flight Management of Future High-Performance Aircraft

DAVID M. PETRIE*
The Boeing Company, Seattle, Wash.

A developmental program to demonstrate the feasibility of automation as a means of improving the safety and profitability of commercial aircraft operations in the post-1975 era is underway. The integrated flight management system described herein employs a central computer onboard the aircraft to 1) control flight-path segments to precisely follow a flexibly programmed spacetime profile; 2) effect configuration control of the airplane and its principal subsystems; 3) automate the preflight check-list and equipment switching; 4) drive a multimode cathode ray tube display for monitoring equipment status and navigational situations; 5) effect automatic placarding for semimanual modes of flight operations; and 6) compute Mach number, effect c.g. control, store and display emergency operating procedures, and perform other similar functions that are amenable to centralized computing. Manual reversion for all automated functions is available. A similar increase in computerization of the air traffic control system is needed to best exploit the precise navigation and control capabilities of the automatic flight management (AFM) airplane in improving traffic flow and airport utilization. The need for planning is underscored by the many civilian and governmental organizations that desire to implement their related improvement programs in a coordinated way.

I. Introduction

THE role of the pilot in flight management of commercial aircraft has developed over the past four decades in quite logical fashion. As aircraft size, complexity, and speed have increased, we have found ways to display more information to the pilot, we have provided control surface power boost to augment his limited physical strength, and we have devised course-holding autopilots to free him from a routine task. The need to accelerate this evolution is underscored by a consideration of the following comparison in Table 1 between a typical commercial transport airplane of today and tomorrow's aircraft, such as the supersonic transport (SST).

Furthermore, runway acceptance rates and traffic handling procedures, as we know them today, exact an impressive toll on payload capacity and usable range, for aircraft like the SST, due to the large fuel reserves required. Precise navigation afforded by inertial navigation, digital data links between ground and airborne systems, and new autoland aids will avail a more orderly traffic management situation, relatively free of lengthy traffic holding patterns.

An analysis of the man/machine relationships which will be encountered in the operation of future aircraft has made it apparent that a modified philosophy of the role of the crew may be needed for operating large, fast aircraft, especially in the air-space environment circa 1980. This requirement is not generated specifically by supersonic speed, but by a com-

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* Engineering Manager, Automatic Flight Management Research Project.

Table 1 Subsonic-supersonic comparison

$6 million	→ $35 million	Airplane value
180	→ 350	Human lives
Mach 0.9	→ Mach 2.7	Navigation event rate
7 million (1965)	→ 20 million, 1975	Aircraft operations

plex of factors that affects the safety and economics of commercial aviation. These factors include airport congestion, air-space utilization, instrument displays, landing approach systems, physiological and perceptual capabilities of the crew, and the complexity of the modern cockpit.

The rationale for developing an AFM system is, in part, to free the crew of certain routine and error-producing operational functions by relegating the performance of these functions to machines. Automation of routine manual tasks can relieve workload pressures and provide time for the crew to stay more completely abreast of the total flight situation. Recognizing the necessity of reducing the crew workload, specific nominations for automation are based upon: 1) improving operating safety; 2) minimizing human error as a factor in system reliability; and 3) the economics of the particular automation in question.

Figures 1 and 2 compare the relationship between man and the machine for the subsonic airplane of today with that of the more automated aircraft of the near future. It should be noted that man is the ultimate authority in both cases, and that the automatic flight management concept described herein is more evolutionary than revolutionary.

II. Man-Machine Relationships

To best identify those functions that the flightcrew should perform and those that should be done by automatic equipment, the capabilities and limitations of man vs machine may be compared. The human capability to respond to a wide variety of stimuli and to store and recall large amounts of data are features that should be exploited in any scheme of automatic flight management. The machine, on the other hand, is more accurate and is capable of processing routine data much more rapidly than is man. A gross conclusion is that those events that can be scheduled to occur as a result of a given set of measurable input data should be handled by the machine, with man's role being elevated to that of executive management—a role in which his unique ability to generate a decision from an array of loosely related data that he has never seen before in any previous instance is best employed.

Monitoring

One of the dangers inherent in excessive automation is that the flightcrew in a passive monitoring role may be lulled into a relaxed condition from which they cannot recover fast enough to take over manual control when the need arises. There have already been incidents of this type occurring in today's commercial operations while under cruise autopilot control. Since there is evidence that human reaction time is increased on the order of 40% by being made ready to respond, the use of active monitoring through use of computer-driven displays and associated controls will keep the crewmembers apprised of the status of normal system operation, as well as give them anticipation of a possible requirement for crew action. An example of how AFM can actually improve crew reaction is the case of an impending engine malfunction, due to decaying performance of certain subsystems within the engine. This would be detected by a computer operation that compares the various engine and inlet variables with an equation that defines normal operation at the flight condition in question.

Since most monitoring tasks are accomplished by visual or auditory watchfullness, another aspect for consideration concerns man's performance in vigilance tasks. One of the most consistent findings associated with monitoring of infrequent events is that both performance accuracy and reaction time increase with time. Vigilance proficiency, either visual or auditory, shows the greatest decline during the first half-hour of watch. This implies that the crew monitoring situation should be designed so that continuous watch is not required. Yet, as mentioned previously, the monitoring situation should keep the crew continuously apprised of the state of the system so they can respond appropriately when a requirement for action arises. These two requirements tend to be contradictory, illustrating the need for further developmental testing under operating conditions.

Table 2 Crew workload reduction

Flight phase	Percent reduction—AFM Captain	First officer	Flight engineer	Crew combined
All flight phases preflight and postflight	34.5	43.8	58.0	45.4
Flight phases only	34.0	37.2	40.0	37.0
Takeoff only	27.5	27.8	31.2	24.5
Approach and landing	10.2	27.6	31.0	24.5
Takeoff and landing combined	21.2	27.7	31.1	26.4

Crew Workload

An analysis was conducted to compare the estimated crew workload in the AFM concept with the crew workload of today's subsonic commercial jet airplane. Table 2 summarizes the results as a function of crewmember and flight phase. It should be noted that the flight phase that includes the preflight checkout shows the greatest workload reduction because of the automatic preflight checkout feature of AFM. The high speed and thus high earning power of the SST underscores the need to reduce to a minimum wasteful turnaround time at the end of each route leg. Since manual checkout of more than 1300 displays and controls on the SST within 20 min approaches impracticability, the time-shared use of a central computer is an attractive solution. Poststart and taxi checklists in today's operations also contain many redundant items

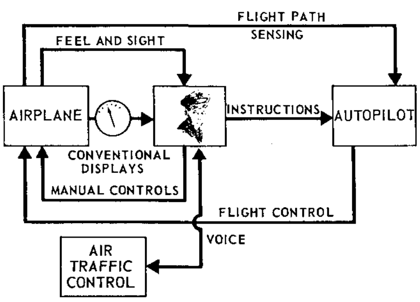

Fig. 1 Today's airplane.

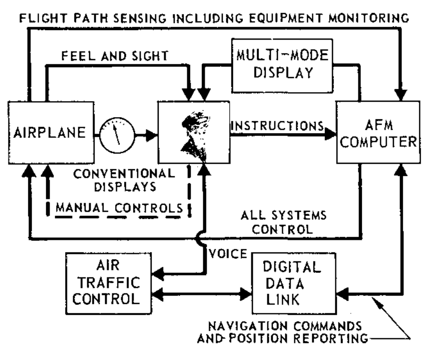

Fig. 2 AFM airplane.

that are checked and rechecked to enhance human reliability. Automatic annunciation of the exceptions would reduce crew workload and allow crew concentration on the management of the aircraft movements. A major workload item during this phase is generated by the voice communications required between the crew and the runway traffic controller. Replacement of routine voice communications by a digital data link substantially reduces this workload.

The 2 min subsequent to brake release in takeoff are the highest period of crew workloading in the normal profile, with the possible exception of pilot workload during the final 30 sec of the low-visibility approach and landing. The impact of an emergency occurring during takeoff produces a dangerous overload, sometimes leading to an improper decision to either abort the takeoff or continue. If the crew workload is reduced to permit concentration on exceptional or abnormal requirements, the likelihood of crew saturation will be greatly reduced. The most critical period of the climb, in terms of today's workload, is in the initial phase involving departure maneuvering to get to the planned course. Much of the workload that develops early in the climb results from changes to the filed and approved departure routing. These in-flight changes generate large communications loads. The aforementioned data link system, coupled with its ability to automatically transmit continuous self-position data to the local traffic controller, would significantly improve the efficiency of traffic control. Climb schedules are based upon parameters that lend themselves readily to computerized control inputs.

During cruise flight, abnormal conditions that demand immediate correction, as well as routine monitoring activities, are prime candidates for automation. This is already being done to some extent with conventional autopilots. Man can then be introduced into the loop efficiently to perform the surveillance and manual backup functions.

Workload buildup in descent and initial approach is the inverse of workload in climb. Navigation precision, communication loads, and configuration adjustments increase as the terminal area is approached. The most critical phase of flight, from the standpoint of safety, is the final approach and landing.

III. System Description

The conceptual bases used to synthesize an automatic flight management system can be best understood by considering mankind, who has evolved a remarkable control system. All the routine processes, such as blood circulation, respiration, minor repairs, locomotion, and data filtering are performed at the subconscious level, partly by local controls and partly by the brain; they intrude on the consciousness only when necessary, as to warn of hunger or of a wound. This has freed the conscious mind for nonroutine activities, such as watching for subtle danger signals and deciding on what action to take. The conscious mind occasionally overrides the automatic system, as when breathing is stopped temporarily while swimming under water.

Table 3 Design approach comparison

CONVENTIONAL APPROACH	FUNCTION	AFM APPROACH
FLIGHTCREW	PREFLIGHT CHECKLIST, EQUIPMENT ACTIVATION NAVIGATION MODE SWITCHING AND AIRPLANE CONFIGURATION CONTROL	AFM COMPUTER
MACH-ALTITUDE DISPLAY WITH MANUAL INPUTS FROM PILOT	MACH-ALTITUDE PLACARDS AND SONIC BOOM CONTROL	AFM COMPUTER AND MMD DISPLAY
INSTRUMENT LANDING SYSTEM (ILS)	AUTOMATIC LANDING SENSORS	NEW HIGH-FREQUENCY SENSING SUBSYSTEM
AUTOPILOT	AUTOMATIC LANDING GUIDANCE COMPUTATIONS	AFM COMPUTER
CENTRAL AIR DATA SYSTEM (CADS)	MACH-ALTITUDE COMPUTATIONS	AFM COMPUTER
IMU PLUS SEPARATE COMPUTER	NAVIGATION SENSORS	IMU PLUS AFM COMPUTER
INERTIAL NAVIGATION SYSTEM (INS) COMPUTER	CRUISE PATH CONTROL	AFM COMPUTER
AIRBORNE INTEGRATED DATA SYSTEM (AIDS)	EQUIPMENT MONITORING	AFM COMPUTER WITH MMD DISPLAY
SEPARATE CG COMPUTER	CENTER-OF-GRAVITY CONTROL	AFM COMPUTER
ELECTRIC COMMAND SYSTEM (ECS)	ELECTRIC CONTROL COLUMN INPUTS TO FLIGHT CONTROL	FCE
STICK SHAKER	G AND ALPHA LIMITING	FCE G AND ALPHA LIMITER
STABILITY AUGMENTATION SYSTEM (SAS)	AIRFRAME STABILIZATION	FCE
MASTER SERVO, SAS SERVO	SUMMING AND BLENDING OF CONTROL SURFACE ASSIGNMENTS	FCE
PRIMARY FLIGHT CONTROL	FLIGHT CONTROL MECHANICAL BACKUP	DECLUTCHED CABLES

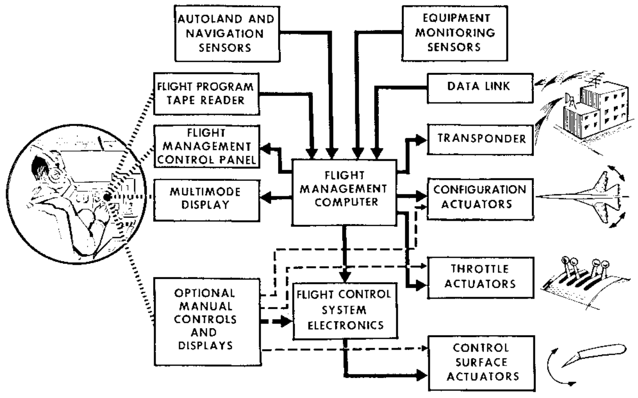

Fig. 3 Automatic flight management system.

This study of the desirable method for controlling a complex airplane, such as the SST, has led to a similar system in which the routine operations are performed automatically, partly by local, specialized control systems and partly in a central digital computer. The automatic system keeps the crew informed of what it is doing and what the status of the airplane and its equipment is—emphatically, in the case of urgent information. The crew has the option of assuming direct control of any function as deemed desirable but is normally occupied in watching for unusual events, assessing the over-all situation, and making decisions. These principles are already being applied to some degree in today's airplanes.

The interconnections and information flow between major sections of the AFM systems are shown in block diagram form in Fig. 3. Inner-loop control of complex subsystems, such as short-period flight control, environmental control, engine throttle and inlet controls, brakes, and landing gear steering is effected locally for safety and technical management reasons. A functional comparison between the conventionally designed navigation and control system and the more centralized computing approach is shown in Table 3.

The redundancy rule followed in this preliminary design is that equipment necessary to the safety of flight is triplicated, with equipment not necessary to the safety of flight being high quality single-thread, backed up by alternate, simpler devices used in conjunction with a manual mode of operation. This safety-of-flight consideration is one of the reasons the flight control electronics (FCE) are separated from the flight management computer, as shown in Fig. 3.

The criteria for inclusion of functions in the central computer are complex, including such factors as type and frequency of computation, need for coordination with other functions, and design and development difficulty. For instance, the inner loops of engine inlet control and the environmental control are not included, because they are best developed and maintained as autonomous systems, not requiring a high degree of coordination with other functions. On the other hand, airplane speed, attitude control, trim functions, and propulsion configuration must be closely coordinated during such critical phases of flight as automatic takeoff, landing, and rollout, and thus are included in the central computer system. Other functions, such as e.g. control, flap setting, and wing-sweep angle, although less critical, are easily automated through the central computer, because the cues used by a human operator in the manual mode also exist within this computer. Similarly, computer comparison and processing of navigational sensor outputs can give the crew a more accurate estimate of navigation position than they could obtain by reading the various dials on these devices themselves, so these functions, in the automatic mode, are performed in the central computer.

The physical components of the automatic flight system include sensors, displays, manual input devices, actuation

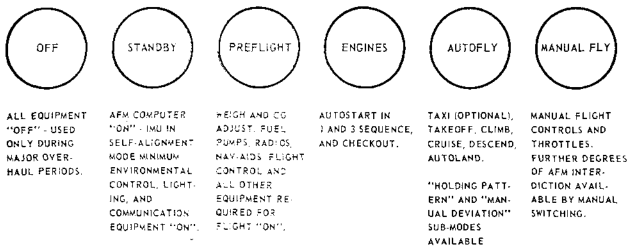

Fig. 4 AFM control panel concept.

systems, and computers. The sensors are similar to those being used in current aircraft (inertial measurement units, radio navigation aid receivers, air data transducers) plus equipment status monitoring transducers as planned for the aircraft integrated data system (AIDS), with provisions for utilization of additional navigation aids (OMEGA, navigation satellites) as they become available. Modifications to the present display system include cathode ray tube (CRT) displays utilizing the capability of the digital computer to generate effective pictorial representations, equipment status and warning indicators, and a printer for computer output. The autopilot input controls have been replaced by a keyboard, used for AFM commands, manual inputs, and interrogation of the computer; there is also a tape reader for flight plan insertion. The flight management computer replaces the primary inertial navigation computer, autopilot, and numerous comparison and computing devices. Executive control of the aircraft is exercised through a mode control panel (Fig. 4) mated to the AFM computer.

A multimode display (MMD), Fig. 5, not unlike a common television set, is used to provide monitoring information to the flightcrew that is peculiar to each mode of ground-based and airborne operations. A conventional array of manual controls and displays is available for handling the abnormal or unscheduled events. Compatibility with the automatic mode of flight management is affected by adding a third position, AFM on, to the normal on-off type of equipment switches, as depicted in Fig. 6.

IV. System Operation

Operating Philosophy and Routine

The operating philosophy of the automated flight management system consists of providing the crew with a choice as to the degree of automation to be used at all times, with an override capability throughout the flight. The flight profile is divided into the following sections, which are shown graphically on Fig. 7: preflight checkout, terminal taxi-out, takeoff, programmed climb, cruise, programmed descent, autoland, terminal taxi-in, and postflight check. Equipment subsystem operation as a function of the flight profile is shown in Table 4.

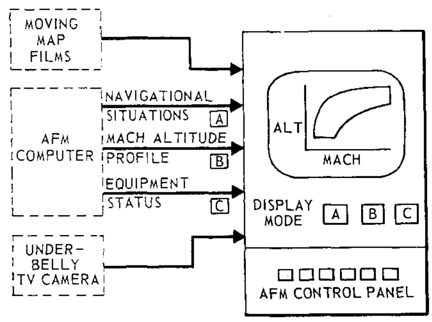

Fig. 5 Multimode display. Specifications: 10-gun, 12-in. cathode ray tube; superimposition of data (film with active data).

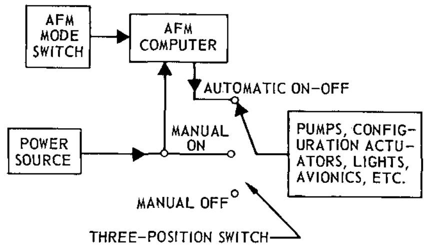

Fig. 6 Manual/automatic control options. Permits override of automated modes; permits descrete energization of equipment with AFM "off."

In addition to the control panel, the flightcrew/computer interface is the multimode display (Fig. 5), plus a tape recorder with printer, and a manual keyboard. The computer is programmed such that the manual keyboard may be used to call up any data in storage for readout on the multimode display. The tape reader is used primarily for inputting data that does not change from flight to flight, such as flap and wingsweep programs, cabin temperature and pressure profile, and radio frequencies. Where digital data link facilities are not available, flight plan data are also inserted via the tape reader and through the manual keyboard. The tape recorder and hard copy printer are used to provide a permanent record of selected navigation parameters and equipment condition as seen through the aircraft integrated data system.

The computer operating routine in the "automatic" mode is approximately the same for all segments of the flight profile. The appropriate guidance computations are performed to generate flight control and throttle commands. In addition, the computer cycles through the checklist are applicable to the current section of the flight profile. Critical checklist items are displayed on the MMD for possible flightcrew intervention. The display may also be accompanied by an audio signal that could be a canned tape message or a simple audio tone. Alternate use of the display-audio combination is a countdown concept to alert the crew of an impending automatic action, such as a wing-sweep change or programmed descent.

The automatic action may then be rejected by the crew, if desired, by placing certain systems in the "manual" mode. For the following section, which describes a typical flight plan execution, both techniques are utilized to alert the crew of significant impending automatic action or required crew action. Less critical action is emphasized using a blinking display, whereas emergency action utilizes a wailing audio tone with the display.

Flight Plan Execution

As the flightcrew readies the aircraft for flight, the flight plan is inserted into computer storage via the data link. This includes clearance status from engine start to takeoff. The inertial measurement unit (IMU) is also ready for flight, since the final item of the postflight checklist from the preceding flight switches the IMU from "operate" mode to the "alignment" mode. This represents the standard or normal ground condition for the SST aircraft, since the AFM computer and the IMU are shut down only during a major overhaul period.

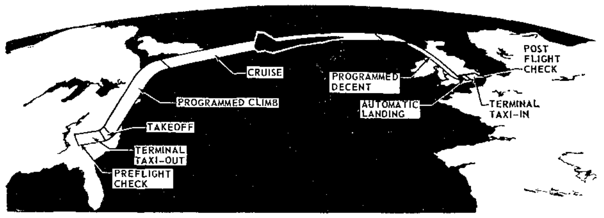

Fig. 7 Flight profile.

Table 4 System operation—flight profile

SYSTEM \ FLIGHT MODE	STANDBY	PREFLIGHT	TAXI	TAKEOFF	CLIMB	CRUISE	DESCENT	LAND
AFM COMPUTER	PROGRAMS INTERNAL LIGHTING AND ENVIRONMENTAL CONTROL	ACTIVITIES EQUIPMENT CHECKOUT; WEIGHT AND CG ADJUST; STARTS ENGINES	COMMANDS AUTOSTEER OF LANDING GEAR	PROGRAMS THROTTLES AND FLAPS; COMPUTES TAKEOFF REJECTION	WING-SWEEP AND CG CONTROL; SONIC BOOM PROFILE CONTROL	PRECISE FLIGHTPATH CONTROL, COMPUTES OMEGA POSITION	DESCENT PROFILE CONTROL	AUTOLOAD AND ROLLOUT VARIATION
INERTIAL MEASUREMENT UNIT	SELF-ALIGNMENT MODE		DEAD-RECKONS BETWEEN MARKERS	PROVIDES RUNWAY GUIDANCE SIGNALS	VELOCITY AND POSITION MEASUREMENT WITH OMEGA UPDATE	→	→	BACKUP GUIDANCE SIGNAL FOR AUTOLAND AID
AIR TRAFFIC CONTROL AND DATA LINK	COLLATES FLIGHT PLANS AND PREPARES SPECIFIC FLIGHT PLAN TAPES	INSERTS FLIGHT PLAN IN AFM COMPUTER MEMORY	RECEIVES POSITION REPORTS FROM AIRCRAFT VIA COMSAT	COMMANDS PRECISE DEVIATIONS AS NECESSARY	→	→	POSITIONS OF LOCAL TRAFFIC SEAT TO AIRPLANE	→
MULTIMODE DISPLAY		EQUIPMENT STATUS REPORT	UNDERBELLY TV CAMERA	HIGH-RESOLUTION RADAR	MACH VERSUS ALTITUDE	MOVING MAP	LOCAL TRAFFIC	HIGH-RESOLUTION RADAR OR UNDERBELLY TV
FLIGHT CONTROL ELECTRONICS		CONTINUOUS SELF-TEST, ACTUATES SURFACES		RECEIVES STEERING COMMANDS FROM AFM COMPUTER	→	→	→	→
LANDING AIDS			DYNAMIC TEST OF OPERATION	BACKUP CHECK OF IMU				GLIDE SLOPE AND RANGE INFORMATION

Preflight Check

Visual inspection of the aircraft has been performed during and after refueling by ground personnel. The first action of the flightcrew is to verify that the stored flight plan matches a hard copy provided by the dispatcher. This is done using the onboard printer. When this is accomplished, the system is placed in the "preflight" mode. The MMD registers completion of the preflight operation and presents an "engine start clearance" status. This results in an audio tone both inside the cockpit and outside the aircraft. When the flightcrew elects to initiate the "engine start" sequence, one engine is started automatically. After this engine generates sufficient bleed air, the remaining engines are started, also automatically. After these engines and all other equipment have reached operating conditions, the MMD switches first to a "taxi clearance status" and finally to a "taxi clearance" countdown.

The initial time value for the taxi clearance is based on the air-traffic control (ATC) center's estimated flight profile, which is established for each aircraft type when the flight plan is first filed. Prior to first motion, ATC assigns the aircraft a specifically identified cell of moving ground and airspace. Each aircraft operating under precise navigation is fitted into this moving cell, which is continuously updated based on actual flight progress. Position checks are made by a microwave data link that interrogates each aircraft, which, in turn, responds automatically by identifying its flight along with its instantaneous position and altitude.

Taxi and Takeoff

Shortly before taxiing is to be performed, the MMD switches to a roadmap type of display of the airport, stored on microfilm, with radar-derived data of other aircraft occupying the runway being superimposed on the stored presentation. This display mode is the normal one used by at least one of the crew in normal weather and is the sole visual display under zero-zero visibility (category III) conditions. This display includes both the identifying number of the taxi strips and the takeoff runway the aircraft is cleared to use. The flightcrew then taxis the aircraft to the holding point beside the takeoff runway. At this point the pilot calls up a takeoff clearance countdown. The MMD switches to a takeoff mode when the throttles are manually positioned to the "autothrottle" position. The taxi onto the runway and the takeoff roll are programmed by the AFM computer when the countdown reaches zero. The MMD then switches to a display of velocity, pitch angle, yaw angle, and roll angle with respect to the takeoff runway.

The rate of climb is also displayed, and as it approaches the required climb rate for gear retraction, a blinking "gear up" display appears. When the rate of climb reaches a prescribed value, the gear is automatically retracted, and a "gear up complete" display appears. This verifies that the gear has been raised, stowed, and locked and that the wheel well doors are closed and locked. This places the aircraft on a stored rate of climb, with the ground track centered on the projected runway.

Programmed Climb

As the aircraft approaches a stored altitude of 200 ft above the runway, the MMD displays a blinking "climb profile" A(CP-A). Certain configuration information is also displayed, such as wing sweep, flap settings, c.g. travel, and fuel transferred. As the velocity increases, the flaps are automatically raised, and the current values of these parameters are displayed. As the velocity reaches a stored reference value, the flaps are completely raised, and a "flaps up" display appears. As this altitude is passed, the aircraft starts CP-A, which is an optimum noise abatement profile based on the present and predicted aircraft and meteorological parameters (weight, fuel flow rate, ambient temperature, etc.). During the programmed climb, a CP-A status display appears on the MMD along with the aircraft error, if any, in both Mach number and altitude compared to the stored profile. These errors should be within tolerance and are an indication to the crew as to the tracking performance of the automatic control system. Course performance is shown by displaying the aircraft Mach-altitude position with the selected climb profile (Fig. 5). After the aircraft accelerates through the transonic phase and approaches the stored altitude and Mach number for cruise, the MMD switches to a "cruise" display.

Cruise

In the cruise mode, the aircraft holds to the stored altitude and Mach number for cruise and the updated flight plan heading. These parameters may have changed during takeoff and climbout due to weather, aircraft emergencies, or traffic conditions in the terminal area. Altitude, Mach number, and heading error are displayed throughout the cruise phase, along with predicted fuel reserves at the destination. Such reserves are continuously computed on the basis of current operating data and stored data, with the latter being updated as new information becomes available. Fuel reserve computations are also computed for all alternate destinations, and any of these may be called up from storage for display. This is true of any pertinent data set that exists in computer storage. A limited number of data sets may be selected by the crew for continuous display. A different set may be displayed at the flight engineer's position. These data might include skin temperature, weather (clear air turbulence detection), position, remaining flight time, or time-to-descent coordinates.

As the descent coordinates are approached, the MMD switches to "descent profile" B (DP-B).

Programmed Descent

As the aircraft crosses the descent coordinates, variables controlled during descent are positioned to their stored references (wing sweep, spoilers). Aircraft position with respect to the selected Mach-altitude profile is displayed graphically as well as numerically, the same as for "programmed climb." Other information, such as wing sweep, c.g. travel, fuel reserves, and aircraft position and heading, may also be displayed during descent.

As the aircraft approaches the final portion of the descent profile, the MMD is switched to monitoring terminal approach data such as hold pattern and altitude, approach heading, approach fix, landing aid lock-on, neighboring aircraft positions (via a digital data link), landing clearance status, landing runway condition, weather—categories, I, II, III, etc. As soon as landing aid lock-on occurs, the MMD switches to a category III—"autoland"—display.

Automatic Landing

As the aircraft passes through the approach fix coordinates, the computer cycles through the landing checklist and configures the aircraft for landing. When the landing gear is down and locked, the MMD switches to monitoring landing data, such as touchdown error, runway heading error, time to touchdown, altitude rate, and wind shear and critical data, such as position and heading data for threatening aircraft in the immediate vicinity.

Information for generating these data is provided by present or improved versions of the ILS, radar altimeter, central air data system, inertial navigator, and a special landing radar on the aircraft. As the time to touchdown reaches 60 sec, the MMD switches to a special radar display or an underbelly TV display. The sensors are aligned such that the runway outlines coincide in a superimposed display. Numerical error data are also displayed for touchdown point, runway heading, altitude, altitude rate, and wind shear. As the aircraft touches down, directional control is gradually picked up by the nose wheel control system. The control mix is determined by wheel loading and air speed. Sensed error information for the ground roll may be provided by the ILS or by electromagnetic cables embedded in the runways. The autoland system reduces the ground speed to taxi speed (V_T) and swithces aircraft control to either automated terminal ground control or manual control by the flightcrew.

Postflight Check

The most significant item on the postflight check is switching the IMU platform from the "navigate" to the "alignment" mode. This is accomplished after all systems, other than the AFM computer and the IMU, have been shut down.

Emergency Operations

Emergency operations with an automated flight management system should be minimal, due to a continuous monitoring of the aircraft equipment with the AIDS concept. Pilot workload, when such emergencies do occur, is reduced by preprogramming the computer for as many emergency procedures as are deemed practical. An example of this is an engine-out condition during takeoff. An uncontrollable delay or loss of thrust in any engine results in a change in the equations for computing control system error signals. This results in a minimum change in flight path as the changing thrust is compensated for through the autothrottle and the flight control system. A simultaneous visual indication and wailing audio tone informs the crew of the condition and indicates the cause insofar as the engine sensors can provide such information. In some cases, additional automatic corrective action could be programmed for safety considerations (e.g., fire). Exceeding preprogrammed limits could produce an automatic shutdown and sealing-off of an uncontrollable engine. Similar examples exist for other systems where preprogrammed subroutines exist in computer storage.

V. Navigation Sensors

Enroute Navigation

The navigation sensors for the automatic mode of flight management consist of an inertial measurement unit (IMU) and radio navigation aids, such as OMEGA. A major question to be answered is whether or not to provide the inertial navigation computation in the AFM computer or in separate computers associated with each IMU. Each method has its own advantages and disadvantages. Providing separate computers does allow a more independent development and testing program for the inertial navigation system. On the other hand, central computation offers a higher degree of flexibility, since the navigation computation, mode control, and self-check programs are easily changed. A possible answer may be a combination system, where each IMU has a simple computer for velocity and position computation.

The AFM computer would provide the mode control, guidance computations (range, time to go, steering commands), position update computations, and self-check and failure detection computations. Each inertial system would also be provided with simple controls and displays for checkout and for backup navigation independent of the AFM computer. The AFM computer could easily be programmed to accept the outputs of one, two, or three inertial navigation systems at little increase in complexity or memory requirement. All inertial systems would have the capability of operating independently from the AFM computer.

The presently recommended system provides all navigation computation in the AFM computer. This concept will be traded with the preceding concept to determine the best approach in terms of operational suitability, reliability, cost effectiveness, and growth potential.

Automatic Landing

The sensing subsystem for automatic landing consists of a new pulse-coded type of range and angle measuring device capable of multiple handling of aircraft at an airport with multiple runways. A backup autoland aid, requiring no ground-based equipment, consists of a high-resolution radar or a scanning infrared sensor. Position and velocity data from the inertial measurement unit is used in both cases to improve the quality of the guidance signal and to protect against hard-over failures during the critical touchdown phase.

VI. AFM Computer

The automatic flight management computer is a general purpose, stored program, parallel machine employing two central processing units with shared use of four memory modules, with an 8192-word storage per module. This central computing subsystem, replacing several separate computers in the decentralized approach, is estimated to weight approximately 140 lb.

The computing subsystem will have multiple memories and multiple central processing units (CPU's). Such a system is very flexible, since it allows for either redundant or nonredundant processing. For example, to control safety-of-flight systems (e.g., autoland) both CPU's will perform the same computation, whereas to control systems not necessary

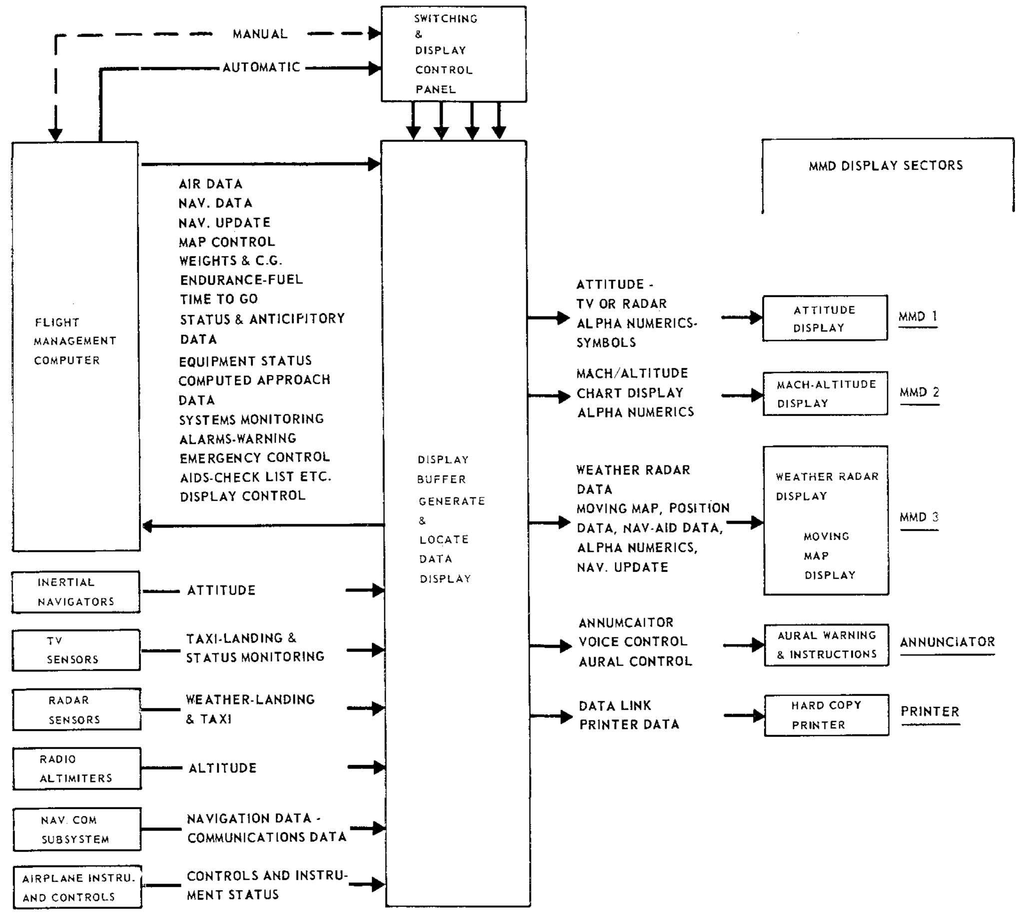

Fig. 8 Display subsystems peculiar to AFM.

to safety-of-flight the CPU's will perform different computations.

Those flight management computer functions considered in this preliminary study include the following: flight profile management, navigation and navigation aids, autopilot/autothrottle, fuel and c.g. management, systems monitoring (AIDS), and display management and emergency control. These functions assume different priorities depending on the flight phase, i.e., takeoff, climb, cruise, approach, or landing.

Flight Profile Management

The flight profile program controls the altitude and the velocity of the aircraft by computing, in real time, the desired velocity and the desired altitude. The presently envisioned flight profile program consists of four modes:

1) The primary mode is based on a space-time schedule that is read into the computer memory immediately before the start of the flight. This schedule would be optimized for the expected conditions along the flight path. A duplicate schedule would be retained on the ground to be used as the flight profile standard for air-traffic control purposes. In-flight updating is possible.

2) The second mode is a manual backup mode that insures that no contraints, such as structural heating, surface flutter or sonic boom, are violated. "Canned" holding pattern submodes are also introduced in this operating mode.

3) The third mode allows for real-time optimization of the flight profile as a function of the currently experienced conditions, such as might be needed for an engine-out or an unpredicted winds-aloft condition.

4) The fourth mode is a simple course, altitude, and speed holding mode in which the azimuth heading, altimeter, and airspeed control loops are closed through the AFM computer. This mode is similar to the autopilot mode in common usage in today's airplanes.

Navigation Position Measurement

The basic navigation system consists of an IMU, supplying aircraft heading and acceleration data to the two central processors, which make two independent computations of aircraft position. The inertial positions are periodically updated by fixes computed from measurements taken from navigation satellites and/or the OMEGA VLF radio navigation system. LORAN C and VOR/VORTAC radio navigation systems can also be used to provide position updates. The desired track is computed from flight plan data stored in the AFM computer memory.

Center of Gravity Management

The primary purpose of c.g. management is to optimize distribution of the fuel during all phases of flight to effect proper trim conditions. It is the basic trim system with vernier trim being effected by the pitch control surfaces through an automatic trim subloop in the short-period flight control electronics (FCE).

System Monitoring

The AFM computer will include AIDS functions and internal self-test as system monitoring functions. The AIDS program provides an over-all aircraft systems monitoring, data comparison, and selected trending capability. Self-test programs and hardware, such as memory parity check, will be used to insure functional correctness of computer operations.

Display Management and Emergency Control

The purpose of display management is to provide the crew with a rapid indication of normal operating conditions and potential or prevailing undesirable operating conditions, as derived from instrument readings. The magnitude of this

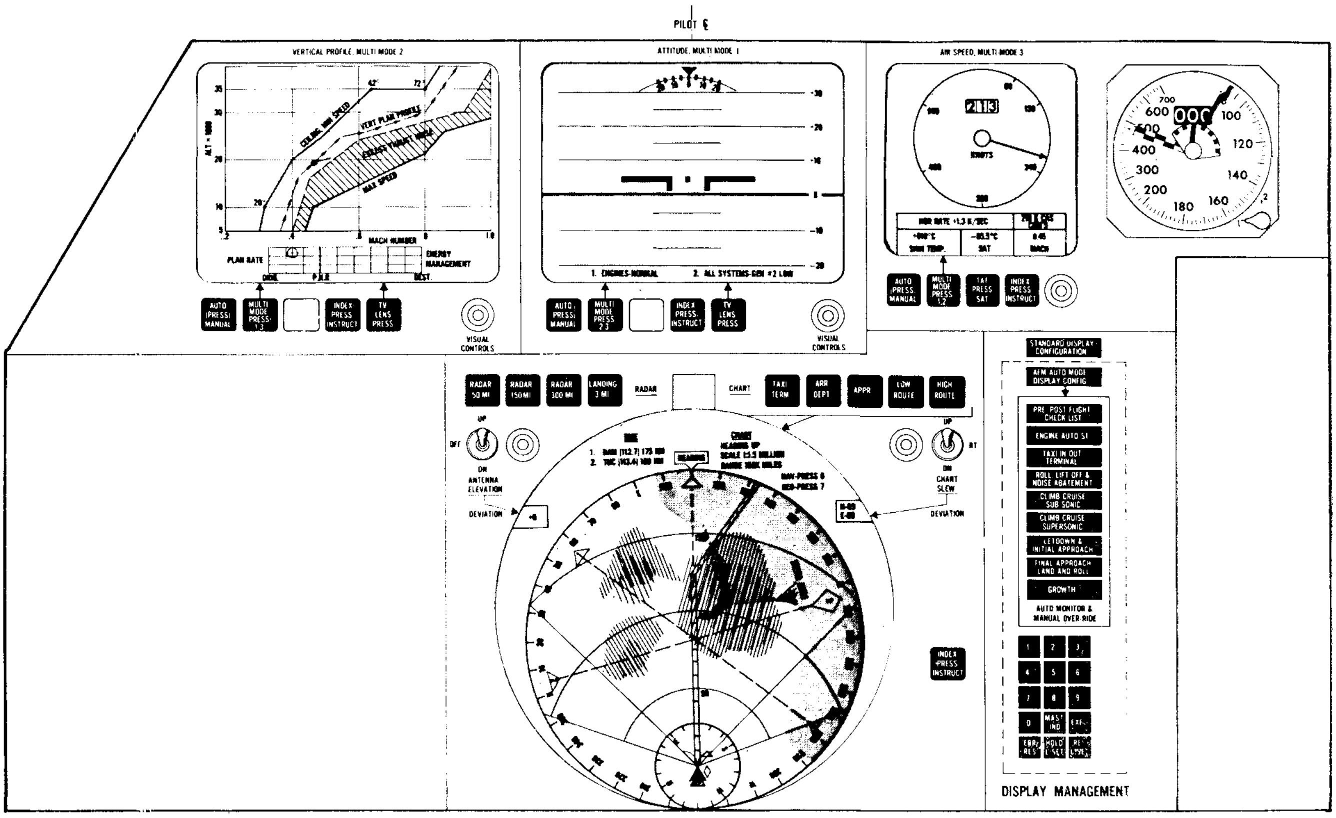

Fig. 9 Pilots AFM display panel climb-cruise subsonic mode.

task has been estimated for 150 instruments sampled at an average frequency of twice each second. A number of general housekeeping functions, such as seatbelt and no-smoking signs, are also handled by the computer.

AFM Computer Hardware

The AFM computer system will be of a general purpose, stored program, parallel, single-address organization. To provide added reliability for the safety-of-flight navigation and autopilot computations, the computer system could consist of two identical central processor units; three to four main internal working memory modules of 8192 words per module; a single solid-state, on-line bulk store of up to 65,526 words; and a common input/output section for analog to digital conversion, digital to analog conversion, and buffering and control as required. Wired redundancy would be used in the input/output section as required for reliability.

The central processor units have programming flexibility through instructions and several working registers, including fast access and temporary storage in a scratch pad memory. A word length of 24 bits for both instructions and data will handle all calculations.

VII. Multimode Display

The multimode display concept is to display primarily the information in special formats as needed at any given segment of the flight profile to keep the flightcrew abreast of the overall flight situation. Since data become information only when they are assimilated, the possibility of losing a message in a clutter of otherwise excellent instruments is minimized.

Although fixed configuration displays, such as needle and dial gages, have many desirable features, only the CRT or flat panel display can offer programmed scale factors, selective superposition of various sensor outputs, and pictorial analog or digital readout.

The MMD display is used to display map data in flight, AIDS, or preflight checkout data on the ground. In addition, it is used for weather radar, and in an emergency it can display airplane attitude information (ADI) in the event of failure of the normal ADI display. When combined information is presented on a single display, it is edited by the AFM computer into the most meaningful hierarchy for each mode of flight operations.

The interface between the aircrew display subsystem components, peculiar to or directly related to the automatic mode of flight and the airplane flight management subsystem, is illustrated in Fig. 8. This interface is effected by a display buffer. The display buffer, under the control of the flightcrew through the switching and display control panel, is included to perform necessary display generation and special storage and switching functions. Raw data and processed information are derived from the various flight management subsystem sources and presented to the display buffer, which then generates and transfers the proper coded message or deflection and video signals to the appropriate multimode display sector. Full flexibility of display format is provided through the switching and display control panel mated to the AFM computer.

Many combinations of data are possible, and care must be taken to automatically present the salient features for any called-for superposition combination. This will preclude cluttering the display. Figure 9 shows three cathode ray tube MMD's in the subsonic climb mode configuration.

The annunciator may use a prerecorded voice message to call the flightcrew's attention to a visual display, to verify the response to the control/command, or to call out critical information, such as altitude, during approach. Nonvoice aural signals are used for warning indicators.

The hardcopy printer would be used mainly in conjunction with a data link for short-term standard operating practice, which saves the pilot's time during the critical pretakeoff and takeoff mode. Accuracy is enhanced, and control-tower-to-plane radio bandwidth is greatly conserved. Other uses of the digital data link are to make rapid and accurate changes in a flight plan or to inform the flightcrew of status and housekeeping data.

VIII. Flight Control Electronics

The flight control electronics (FCE) receive navigation signals directly from the AFM computer, in the normal automatic mode of flight management, or from the pilot's control stick, in the manual mode of flight control, as shown in Fig. 3.

The computations for the short-period flight control system are done in a triplicated computing subsystem separate from the AFM computer, for safety and technical management reasons. Additional safety and comfort features over that provided by most conventional subsonic stability augmentation systems are automatic g-load limiting, automatic prevention of stalls, and active damping of structural modes of vibration.

Pilot-handling qualities are tailored within the FCE to meet pilot approval. A constant stick force per g characteristic is provided at speeds above 250 knots, with a constant stick force per unit pitch rate characteristic becoming dominant at approach and landing speeds.

IX. Development Planning

The technology has already been proven and the individual equipment pieces are available to implement the AFM concept in commercial aircraft operations. The main difficulty ahead stems from the fact that the airline operators, the pilots, the air-traffic controllers, and their respective equipments, are presently oriented to a more manual, less accurate method of navigation and traffic control. Furthermore, as greater degrees of automation are introduced, the total environment must be able to accommodate a mix of AFM-like airplanes, commercial airplanes of today's vintage, and nonscheduled general aviation and military aircraft.

A means for developing the system is under development at the Boeing Company and will be used to demonstrate to the users the potential improvements to safety and traffic flow afford by "AFM," in the broadest context. The facilities of this research program consist of a mobile navigation laboratory (bus), an avionics test bed (airplane), an "ATC" mobile ground station (van) to monitor and control the airplane, and an AFM systems simulator (computers).

X. Conclusions

AFM is not a new and exotic technique requiring technological breakthroughs; rather, it is a natural extension of autopilot applications and air-traffic control procedures as we know them today. The primary reasons for AFM are to increase flight safety and improve aircraft and airport utilization in a commercial aviation environment of ever-increasing congestion. The versatility of the digital computer and the cathode ray tube display, the accuracy of inertial navigation devices, and the new age of reliability afforded by integrated microelectronics, all combine to make AFM realizable in the near future.