Practical Considerations in Commercial Supersonic Transport Flight Operations

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Certain aspects of supersonic aircraft operation have important implications when they are related to commercial transport utilization. Based on a performance simulation and analysis performed under contract to the U. S. Air Force/Federal Aviation Agency (FAA), several areas of considerable interest have been identified and are briefly discussed in this paper. Included in these problem areas are sonic boom control (or more precisely, ground-overpressure limiting), arrival or estimated time of arrival (ETA) control, and fuel management techniques. Based on the quantitative results of this performance simulation, a set of performance tradeoffs has been compiled which points out the obvious inconsistencies that arise from flight procedures that attempt to minimize sonic boom, conform to reasonable air traffic control (ATC) requirements, and result in minimum fuel consumption or minimum operating costs for an SST. Although these procedures are not mutually achievable, they are all interrelated in regard to the systems and techniques required for traffic control integration, navigation, flight path control, and fuel management. Included in the data presented in this paper are tradeoffs associated with direct operating cost (DOC), as well as fuel consumption and airspace requirements. Preliminary mechanization of an airborne system capable of performing the required functions is also presented as one possible approach to the commercial SST vehicle from a practical standpoint.

Introduction

THIS paper concerns itself with the identification of three problem areas related to the practical flight operation of a commercial, supersonic, transport aircraft. These three problem areas are sonic boom control (or more precisely, ground-overpressure limiting), ETA control, and fuel management. These operational problems are related to the arrival and departure phases of a typical SST flight. In order to limit the scope of this paper, the topic of enroute operation has been excluded from consideration.

In general, this paper describes the requirements for, and the mechanization of, an airborne concept called the central electronic management system (CEMS), which performs the major functions of airborne sonic boom monitoring and limiting in conjunction with flight path control, navigation and fuel management, and traffic control integration.

Problem Areas

Although it may seem to some to be presumptuous to discuss at this time the potential problem areas in the operation of a commercial supersonic transport (SST), it is the very fact that this vehicle will be both commercial and supersonic that gives the essence of urgency to the consideration of these problems. Although the airframe and propulsion industries are faced with the formidable technical challenge of designing and producing a safe, efficient, and economical aircraft, there are indeed equally critical operational problems that must be understood and solved in order to make the SST an acceptable mode of transportation. Acceptability, particularly for the SST, includes consideration of the flying and nonflying public as well as the air carriers and their stockholders, the air traffic control agencies involved, and the flight crew personnel.

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It is not the purpose of this paper to present a treatise on all aspects of commercial SST flight operations. Instead, three major operational problems are analyzed, along with general recommendations for their solutions. In addition, the interrelation between these problems and the various phases of a typical SST flight are identified and discussed.

In actuality, all of the subjects covered in this paper have to do with some aspect of vertical navigation. When the speed-altitude envelopes of typical subsonic and supersonic jet transports are compared in Fig. 1, it can be seen what the concept of vertical navigation encompasses. In order to complete a normal supersonic flight, the SST must traverse a speed regime from zero to 2000 mph and back again, hopefully dwelling in the upper speed region long enough to justify all of the expense in dollars and manhours necessary to get it there. Similarly, it must also traverse an altitude regime from zero to as much as 80–90,000 ft in some cases. Unfortunately, because of several constraints not always under the direct control of the designers or even the flight crew, the SST may be required to dwell either in an intermediate speed

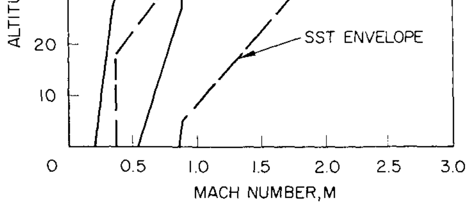

Fig. 1 Flight envelope comparison.

and altitude region or else follow an operationally undesirable profile while transitioning from one extreme of Mach and altitude to another. It is the vertical navigation considerations of sonic boom, air traffic control, and fuel management, which form the basis for this paper.

In varying degree, each of these considerations must be reckoned with during the normal flight. For instance, the departure from the airport, which for the purposes of this paper includes the necessary transition to supersonic cruise conditions, will consume nominally 350–400 miles, 25–30 min, and 60,000 lb of fuel. Although ATC constraints must always apply during all of the phases of the flight, the peculiarities of the SST make the problems of sonic boom control and fuel management the most critical operational tasks during departure. It should be pointed out at this time, as it will be again later during this paper, that the problems of horizontal navigation, vertical navigation, sonic boom control, fuel management, and air traffic control cannot be considered as mutually exclusive. As a matter of fact, analysis reveals that, in order to efficiently achieve even one of these tasks, all of them must be performed. Techniques for achieving this simultaneity of functions will be discussed later.

During the enroute portion of the flight, sonic boom constraints are nominally less restrictive because of the high-altitude nature of the flight. Fuel management techniques and ATC procedures provide the majority of inputs to any vertical navigation functions. Operations during the terminal phase of the flight include the deceleration and descent profile, a series of speed-altitude maneuvers that transfer the aircraft from the supersonic cruise conditions to termination on the airport runway. Of primary importance during this aspect of the flight is sonic boom control and compliance with ATC requirements. The following portions of this paper will discuss those factors of ETA control and flight path management which expand the area considered to be affected by arrival operations out to a distance as much as 500 miles from the terminal airport.

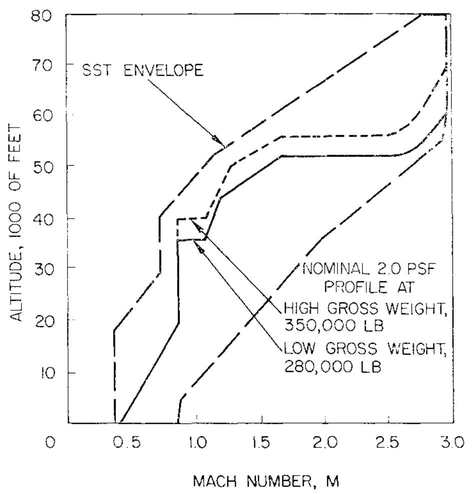

Fig. 2a **Climb profile study.**

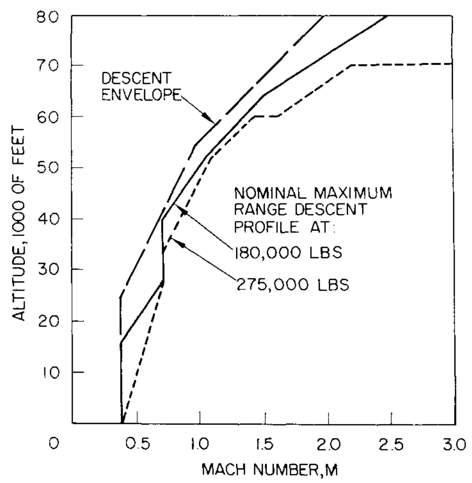

Fig. 2b **Descent profile study.**

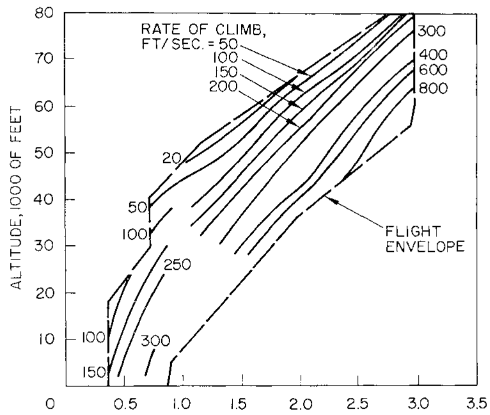

Fig. 3 **Performance capability (350,000-lb takeoff weight, standard day).**

Almost as much noise has been generated on the subject of the sonic boom and the SST as will be generated by the aircraft itself. Semantics notwithstanding, the present nominal requirements for limiting the ground overpressures caused by the sonic boom to 2.0 psf during the climb and acceleration phase and 1.5 psf during cruise, deceleration, and descent, will entail an entirely new type of vertical navigation. As can be seen from Figs. 2a and 2b, the imposition of these overpressure constraints on the nominal performance envelope of the SST drastically reduces the available operational boundaries. Particularly in the case of departure, when the aircraft is fully loaded and the lift effects on the boom are maximum, there exists a rather restricted corridor of profiles in the general region of Mach 1.2 and 50,000 ft. In this region the performance of the aircraft is quite poor because the aircraft is actually operating right in the vicinity of the power-limited minimum speed of the vehicle (where thrust equals drag). Reference to Fig. 3 will indicate how the climb performance deteriorates rapidly as the flight profile is withdrawn from the optimum (minimum) fuel profile on the right, which results in overpressures in excess of 4 psf, to the boom-limited profiles shown on the left.

Again, maintaining cognizance of the direct relationship between the predicted sonic boom overpressure and the instantaneous gross weight of the aircraft, Figs. 2a and 2b illustrate the effect of takeoff and landing weight on the allowable climb and descent profiles. Considering the departure operation in particular, which involves the acceleration and climb profile, it is extremely important to the economics of the aircraft that the actual profile, which is flown, is as close as possible to the boom limit. Any "pad" or safety factor applied to this profile in order to insure compliance with overpressure restrictions forces the aircraft deeper into the region of deteriorated or inefficient climb and acceleration performance shown on Fig. 3. (In particular, the imposition of overpressure constraints moves the flight profile far away from the optimum or minimum fuel profile.) It therefore becomes mandatory to control the aircraft's climb profile as closely as possible to the specific boom-limited profile pertinent to the instantaneous weight of the aircraft. Modification of this profile dependent upon gross weight appears to be a desirable and practical approach.

Another problem exists in the consideration of the interrelation of sonic boom overpressures and climb profile techniques.

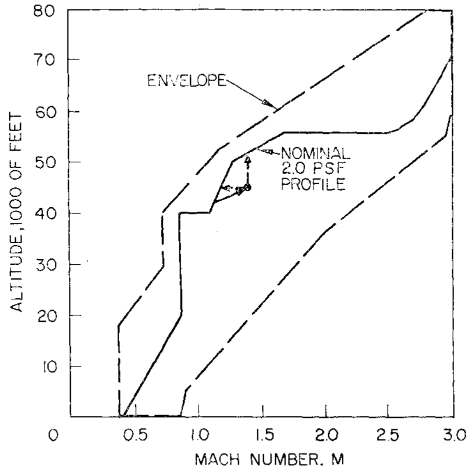

Fig. 4 Recovery from area of excessive boom.

Under the necessary assumption that it is certainly possible, although not probable or desirable, to deviate from the pertinent boom-limited profile, an investigation has been made into the techniques involved in recovering from these undesirable flight conditions. In recovering from a condition where the aircraft is flying too low and/or too fast, as is seen in Fig. 4, two different procedures were simulated to place the aircraft back on the boom-limited profile. The two procedures investigated were deliberately chosen to represent extreme or boundary cases. In one technique, the engines were reduced to an idle power setting, and the aircraft decelerated at constant altitude until the nominal climb profile was reached. In the other case, a constant Mach number climb was initiated at maximum power. Figure 5 illustrates the distance vs overpressure exposure directly under the flight path of the aircraft for each procedure. As can be seen, the idle power deceleration recovery technique results in somewhat less total distance of exposure to overpressure greater than 2.0 psf, approximately 11 miles from the start of the recovery procedure as opposed to 16 miles for the constant Mach number climb technique.

However, when the concomitant fuel consumption penalties are considered, an entirely different picture is presented. The idle power deceleration technique results in a total fuel consumption over a 2500-mile flight of approximately 4000 lb more than the maximum power climb technique. This adverse fuel penalty is associated with a profile that is effectively 0.2 Mach faster at an altitude of 45,000 ft. Since the fuel penalty will be approximately a direct function of the Mach error, the general conclusion can be reached that the maximum power constant-Mach climb technique is best suited for recovery from such a situation. A later section of this paper will discuss a recommended mechanization for accomplishing the combined functions of sonic boom control and optimum fuel management.

Avoiding the problems of enroute flight and cruise control as subjects worthy of separate treatment, although in order to achieve economical and practical SST operations the entire flight must be considered from takeoff to landing, the terminal end of the flight must be given careful weight. For the purposes of this paper, the problems of arrival scheduling and flight profile control are considered as pertinent to the arrival operation. This is not meant to construe the lesser importance of other aspects of terminal area flight, but rather is meant to identify those problems that are in some way considered unique to the SST.

As in the departure operation, the constraint of sonic boom overpressure plays an important part in defining operational techniques. For purposes of fuel economy, it is desirable to descend in idle power over the maximum distance possible. In this case, the resulting profile approximates the left or slow-speed side of the performance envelope as shown in Fig. 2b. However, since in a descent maneuver the present nominal overpressure limit is 1.5 psf, careful control of the descent profile is required in order to avoid exceeding this limit. In some cases, it may not be possible to perform a descent at high gross weights and still conform to this 1.5-psf constraint. This situation may reflect back into scheduling of refueling at a scheduled intermediate stop in a long flight. In this manner, the SST can take off at its initial departure point light enough to enable a landing to be made at the intermediate stop without exceeding the overpressure limit. Refueling would then be required in order to proceed to the final destination. If the aircraft were fueled to capacity at the initial departure, its landing gross weight at the intermediate stop would result in excessive overpressures.

Another consideration in determining descent profiles is necessitated by flight safety considerations. Although it is possible to descend along a profile that is high and slow enough to stay within the 1.5-psf overpressure limit, this profile may fall outside of the boundary of the required performance envelope of the aircraft. The SST, or any vehicle, should never be allowed to enter into a Mach-altitude condition from which it cannot climb and accelerate. A certain level of positive performance must be available for evasive action in case of collision avoidance, basic traffic control procedures, or just general safety criteria. Therefore, another narrow operational corridor must be imposed on the Mach-altitude schedules available for descent profiles, similar to that previously described for departure profiles. Both sonic boom overpressure and aircraft performance are direct functions of instantaneous aircraft weight, which must enter into any determination of vertical Mach-altitude profiles.

In the case of the SST, there is a peculiarity of the performance characteristics of the basic airframe-engine combination that can be utilized to advantage in the solution of a perennial arrival area problem, that of ETA control. The normal procedure, when requested to delay the ETA of an arriving aircraft, is to either slow the vehicle down enroute or else perform a holding pattern to use up time. In the first case, an enroute slowdown means operation at nonoptimum cruise conditions. Particularly in the case of the SST, flight at nonoptimum supersonic Mach numbers is extremely wasteful of fuel. Only in the special case of a variable geometry aircraft can this off-design penalty be minimized, and then optimally, when an attendant change of cruise altitude accompanies the required change of cruise Mach. Holding patterns are even more wasteful of fuel, since even if the aircraft is held at optimum endurance conditions of Mach and altitude, any fuel burned while holding is consumed without benefit of distance flown, and therefore the fuel is effectively thrown away.

The feature of the SST which makes feasible a new concept of ETA control is the ability of the aircraft to cruise at a peak efficiency, either subsonic or supersonic. For a particular simulated Mach 3.0 design point fixed geometry aircraft, it has been found that these two operating conditions occur at $M = 0.88$ and $M = 3.0$, respectively. With this basic assumption of comparable cruise efficiencies, the concept

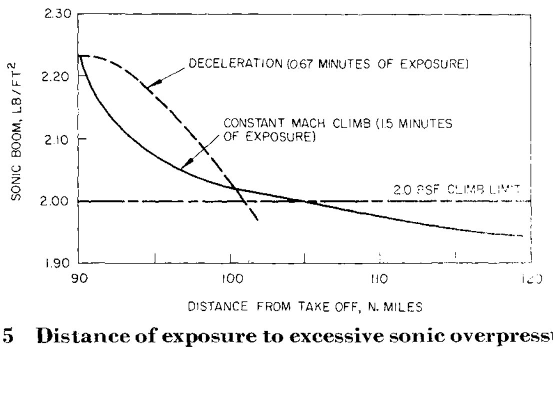

Fig. 5 Distance of exposure to excessive sonic overpressure.

speed mixing can be applied to achieve a broad range of ETA control with a minimum of fuel consumption penalty. Figure 6 illustrates the results of a simulation incorporating this speed-mixing ETA control technique.

In the case where no delay is required, the aircraft will perform a supersonic cruise followed by a normal, maximum range, idle power descent to the terminal area as shown in Fig. 7. The profile to be followed would be defined by considerations shown in Fig. 2b, and the descent would be initiated at the distance from termination defined by the particular profile and aircraft gross weight. If a delay or change in ETA is desired, then the average cruise speed can be reduced by mixing maximum range efficiency supersonic cruise and maximum range efficiency subsonic cruise, as shown in Fig. 6. In this case, the descent to subsonic cruise conditions would be initiated at the proper distance-to-termination, so that the average cruise speed will result in the desired ETA.

As can be seen from Fig. 6, there is a penalty incurred in using the speed-mixing technique to achieve an ETA delay. This fuel penalty is basically a direct function of the required delay time. However, Fig. 6 also shows the comparable fuel penalties associated with holding pattern. In order to provide complete information, a supersonic ($M = 3.0$) holding pattern was also simulated, even though the turning rates at this speed are so low (0.37°/sec) that an inordinate amount of time would be required to complete even one typical race-track-type holding pattern. For the purposes of this simulation, the total fuel consumed in the holding pattern was computed on the basis of the desired time in the pattern, regardless of the actual heading before and after the pattern was executed. However, recognition was given to the increased fuel requirements necessitated by holding speed during a constant altitude turn.

In general, it can be stated that the saving in fuel which can be achieved by use of the speed-mixing concept is of a magnitude to warrant further consideration of this technique. It should be noted that implementation of this procedure involves the initiation of the deceleration and descent profile at distances up to as much as 600 miles removed from the terminal point for desired changes in ETA of 20 min. Descent into and mixing with existing subsonic jet traffic entails the consideration and incorporation of changes in navigation and traffic control procedures. A subsequent section of this paper will outline one suggested means of achieving this combined profile control and traffic integration task.

Potential Solutions

The preceding paragraphs have attempted to identify some of the foreseeable problem areas in the realm of commercial, supersonic, transport operations. However, just to recognize the existence of a problem is in itself not a solution. There must be formulated some practical and economically justifiable means of overcoming these problems if the SST is ever to become a commercially acceptable mode of transportation.

As mentioned previously, the subjects discussed in this paper, namely, sonic boom control, ETA control, and fuel management, are all involved in the mutual consideration of horizontal and vertical navigation. Fuel management during the departure procedure requires precise and continuous determination of an optimum speed-altitude profile subject to sonic boom constraints. Involved in this determination of speed-altitude profiles is such information as present Mach and altitude, cruise Mach and altitude, ambient temperature (not only where the aircraft is presently located, but also the horizontal and vertical temperature profile along the desired line of flight), present aircraft weight and fuel load, and in some cases, distance-to-go is considered.

Previous experience with fuel management functions for high-performance supersonic aircraft has indicated the existence of fairly well-defined general control laws that define minimum fuel profiles. These control laws can be expressed in most cases as analytical functions of the previously mentioned variables, with the form of these functions controlled by the performance characteristics of the airframe-engine combination. A detailed performance analysis of the aircraft's operating characteristics can be performed on an IBM 7094 or comparable computer using mathematical optimization techniques such as dynamic programing. Once these basic optimum control laws have been established, the next step in developing an operational technique is the mechanization or performance of these procedures. However, before this can take place, the peculiarities of SST operation impose additional restrictions in the vertical plane of navigation.

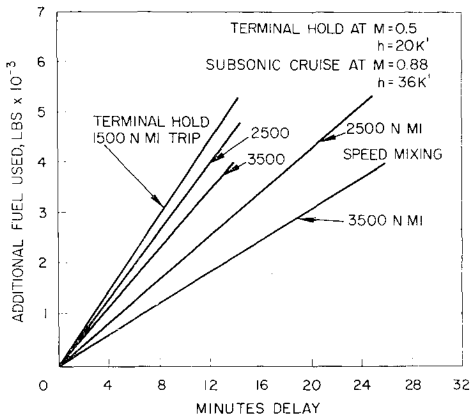

Fig. 6 Comparison of fuel penalties, terminal hold vs speed mixing.

Present analytical techniques that are used to predict the sonic boom overpressures caused by a supersonic aircraft include the consideration of a number of factors. The starting point, of course, is the physical configuration of the aircraft, including functions of the lift and volume distribution and the length of the vehicle. For any given aircraft geometry these values are fixed, although with a variable geometry aircraft, they will vary with the wing sweep, for instance. However, the other factors that affect the predicted overpressure are all continuous variables during any particular flight. These parameters include Mach, altitude, atmospheric conditions from the present aircraft altitude down to ground level (particularly the vertical distribution of wind, pressure, and temperature), flight-path angle, aircraft weight, and normal load factor (caused by pitching or turning maneuvers). One form of the basic overpressure prediction equation is

$$\Delta p = K_1K_2p\beta/(y/L)^{3/4}[1/(\beta \cos\gamma + \sin\gamma)]^{3/4}$$

where

K_1 = reflectivity constant, assumed = 1.9
K_2 = $f(\beta C_L)$, defined by vehicle lift and volume distribution

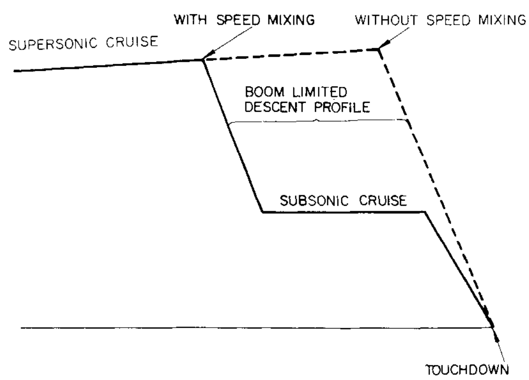

Fig. 7 Descent profile with speed mixing for delay.

y = tape-line altitude
L = aircraft length
p = ambient pressure at $y/2$
β = $(M^2 - 1)^{1/2}$
M = Mach number
γ = flight path angle
C_L = lift coefficient, including effect of maneuvering flight
Δp = sonic boom overpressure, psf

In the preceding equation, the factor K_2 can provide the corrections dictated by effects of a particular airframe configuration, including consideration of wing position in the case of a variable geometry aircraft. Theoretically every wing position or sweep angle defines a new lift and volume distribution specifically related to the particular aircraft configuration. Therefore, a continuous family of K_2 curves could be directly related to the instantaneous wing-sweep angle or other airframe geometry variable. In any instance, for the particular aircraft under consideration, initial theory and wind-tunnel testing can define the K_2 curves pertinent to each possible geometry. In this manner, the best possible approximation to the overpressure prediction equation can be introduced.

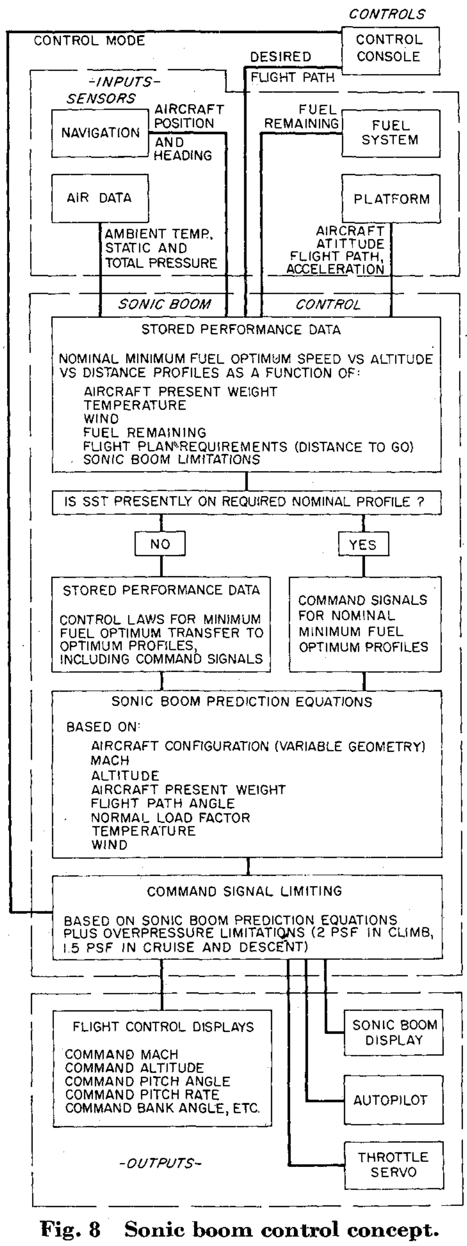

Fig. 8 Sonic boom control concept.

The need for controlling the trajectory, or profile, of the SST so that minimum fuel is consumed while a given sonic boom limit is not exceeded has been discussed previously. Through the use of an onboard data processor, there has been developed a technique for automatically and continuously achieving this over-all requirement. Figure 8 illustrates the mechanization of this concept.

The primary requirement for optimized flight is the knowledge, from each point in the state space (the coordinates of the state space are those variables that describe the SST, such as Mach number, altitude, weight, angle of attack, etc.) of the optimum trajectory to the destination (which will usually be either a supersonic cruise condition or else a terminal Mach-altitude condition). This optimal trajectory would be determined by the data processor in the following manner. (In order to conveniently refer to the system involving an onboard central data processor interconnected with sensors, controls, and displays, the name CEMS has been given to the entire system.)

Let us assume that the aircraft at some time t_i is flying along the trajectory, which, as computed by the CEMS, is nominally optimal for the current values of the SST state variables and the current atmospheric conditions. As time elapses, however, the aircraft may no longer be on the desired path. This could be a result of changes in external conditions such as temperature or wind, or of deviations caused by manual control perturbations, or accumulation of autopilot error. Also, the desired path may be different from the previously predicted boom-limited optimal trajectory because of changes in the sonic boom propagation caused by changes in atmospheric conditions. Closed-loop control is accomplished by the CEMS as follows: At time $t_i + 1$, Δ sec after t_i, the proper sensors are interrogated to determine the current relationship of the vehicle to the nominal Mach-altitude profile. If no deviation has occurred, then the CEMS continues to generate commands and/or displays to continue the vehicle's flight along this profile. If some perturbation has occurred, then the minimum-fuel flight profile transfer control laws are utilized to generate commands to put the aircraft back on the desired profile. At the same time the sonic boom prediction equations are utilized to determine the current overpressure being generated. Based on the results of the overpressure computations, command signal limits are imposed on any profile transfer commands to insure minimum exposure to excessive overpressures.

During manual operation of the aircraft, the CEMS would continuously compute and display the value of overpressure currently being generated. This display feature would also be employed during automatic flight to profile monitoring capability for the pilots. In automatic, or autopilot-coupled, operation, where the CEMS computer is controlling the flight path of the aircraft, perfect system operation in standard day atmospheric conditions would result in flying a profile which consumes the minimum amount of fuel without exceeding the nominal overpressure limit. Under perturbed or nonstandard conditions, the CEMS will still provide commands that, if followed, will result in minimum practical fuel consumption and minimum exposure to excessive overpressure.

Again, considering the projected role of the CEMS computer as a central data processor performing a variety of airborne functions including horizontal navigation, the concept of ETA control in the arrival zone becomes relatively simple. Referring to Fig. 7, the following discussion will illustrate the technique involved.

In normal or no-delay situations, the SST will be cruising at supersonic speeds and best cruise altitude. Since the CEMS computer is continuously performing position-determination computations from navigation sensors such as VOR-DME, it is at all times aware of the distance to go to destination. Similarly, since this same computer is used to determine and control to specified maximum-range boom-limited descent profiles, it is also cognizant of the time and distance required to perform the deceleration and descent maneuver. This information is part of the performance data stored in computer memory. Therefore, one function of the CEMS is to compute and display the current ETA at the designated destination based on total distance-to-go, present Mach and altitude, current gross weight, and current clock time. Using a computer input control that varies the projected time to be spent in the subsonic cruise mode, the average cruise speed can be varied based on the relative times and/or distances spent in subsonic and supersonic cruise. This average cruise speed therefore directly relates to the elapsed time-to-destination and consequently to the ETA.

Still referring to Fig. 7, it can be seen that, as the computer input control is varied to increase the subsonic cruise time, the point at which the initial descent from supersonic cruise to subsonic cruise is initiated moves away from the destination. At the same time, the ETA keeps increasing because of the lowered average cruise speed. The flight crew member operating the computer input must merely continue to increase the subsonic cruise time until the ETA readout from the computer agrees with the ATC-requested ETA. For this particular combination of subsonic and supersonic cruise times, there exists a unique solution for the distance from destination at which the initial descent to subsonic cruise conditions must be initiated. When the aircraft's present position coincides with this distance-to-go, which is continuously calculated by the CEMS computer, the aircraft is directed to descent, either by command displays or else by coupling of the computer with the autopilot and possibly the throttles. The descent and subsequent flare-out to subsonic cruise conditions is performed with the same sonic boom limiting feed-back control concept previously described. The final descent from subsonic cruise to terminal area is initiated in a distance referenced manner similar to the supersonic descent.

The over-all effect of this functional performance of the CEMS is to provide for precise control of the altitude vs distance descent profile of the aircraft, with the additional coordinated provision of speed vs altitude control in order to limit the sonic boom overpressures. In order to simultaneously and automatically achieve these two results, the CEMS computer must be coupled to both the autopilot and throttles. Identical functions have been performed in military aircraft with the computer-autopilot coupling providing flight profile control and the computer providing speed commands that were accomplished by manual control of the throttle by the pilot. Such a system could certainly be employed for the SST.

Conclusions and Recommendations

When the various functions of sonic boom control, ATC or ETA control, and fuel management are studied from the standpoint of potential mechanizations, the concept of the CEMS becomes a serious consideration. Certainly, a data-processing, computing, and control requirement exists in the departure area when the problems of determination of optimum fuel speed-altitude profiles are faced.

There are two obvious means of handling the determination of optimal trajectories. One is by table lookup and interpolation of stored trajectories that were precomputed, either by a CEMS computer or on another computer, such as an IBM 7094. The other way would be to compute new trajectories during the flight. It should be noted that, although the latter would avoid interpolation between trajectories and therefore be more accurate, time of computation may preclude this approach. The algorithm used to generate these paths could be developed from the theory of dynamic programing or possibly from the method of steepest descent. In either case, a high-speed, general purpose, digital computer would be required in the aircraft.

The dependence of these operational functions of sonic boom control, ETA control, and fuel management on common source of computer or sensed information lends additional weight to the suitability of the CEMS concept employing a central digital computer. If the CEMS computer is performing the horizontal navigation task, including techniques of accurate area navigation using cross-checked navigation inputs, the vertical and horizontal navigation functions can be coordinated to provide for completely integrated and optimized flight profiles from takeoff to landing. Traffic control integration would be greatly simplified, cockpit workload reduced, and operating economics greatly improved.

Serious consideration should be given to the necessary ground-based simulation and flight testing required to perform a final evaluation of the CEMS concept. Development of the integrated system should be carried on concurrently and in cooperation with the development of the basic aircraft. The final definition of the specific function and techniques to be mechanized within a CEMS can only be performed after careful evaluation of the over-all implications into airborne equipment requirements, cost, and reliability. Similarly, the implications into not only the airborne operating procedures, but also the ground-based ATC procedures and equipment changes, must also be studied. However, all of these facets of the many-sided SST question must be investigated before practical, commercial, supersonic, transport flight operations can be performed on a regularly scheduled basis.

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