13. INITIAL FLIGHT EXPERIENCE WITH THE XB-70 AIR-INDUCTION SYSTEM [U]

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SUMMARY

The preliminary results and developmental problems from flight tests of the XB-70 air-induction system are briefly reviewed. The system is generally satisfactory, is adequately matched to the engine flow requirements, and can be controlled for the various flight ranges. Inlet unstarts at cruise Mach number constitute a new problem for high supersonic aircraft seriously affecting the dynamics of the inlet and airframe.

INTRODUCTION

The two XB-70 airplanes have been flying for many months. Even though many flights have been conducted for the purpose of developing and demonstrating the airplane systems, a significant amount of research data has been obtained. The importance of inlet performance and its direct influence on overall vehicle performance has been very apparent during the early XB-70 experience as it surely will be on future airplanes incorporating similar air-induction systems.

Future air-breathing aircraft cruising at Mach numbers of 2.2 and greater will very likely incorporate mixed compression inlets for better propulsive efficiencies. The XB-70 air-induction system is one of the first of this type to reach flight status. The initial experiences with the performance and operation of the inlet are reviewed in the present paper. This paper presents some of the operational experience with the air-induction system of the XB-70 airplanes acquired during their initial flights. The physical characteristics and principles of operation of the inlet are described, and the test ranges in regard to vehicle and inlet configuration are given. A summary of the inlet performance achieved to date is presented. Finally, there is a brief discussion of inlet problems, many of which have resulted as a part of the early effort to investigate the operating envelope of the inlet and to check out its control system.

DISCUSSION

Figure 1 is a photograph of one of the XB-70 airplanes in low Mach number flight alongside a chase plane. Note the proportion of the XB-70 integrated inlet-engine system to total airplane volume. The length of the inlet from the leading edge to the compressor face is about 90 feet. The primary duct is large enough for a man to walk upright almost to the engines.

A large number of supersonic flight hours have been flown with the two XB-70 airplanes. Both have flown to Mach number 3 with the number two airplane flying most of the high supersonic flights. The more significant flight hours from the inlet viewpoint are those obtained at speeds above Mach number 2 where the inlet is started, which means that supersonic flow exists in the forward part of the duct and a normal shock exists downstream of the inlet throat. In this region the operation of the inlet system becomes more critical in that it affects not only the efficiency of the propulsion system but also the dynamics of the airplane. Thus, a preponderance of inlet testing has been done in this region as evidenced in figure 2. The enclosed area is the envelope of overall flight experience to date. Symbols are used to represent major planned and unplanned inlet events as follows: unstart, a rapid expulsion of the internal normal shock; duct buzz, an unstable cyclic flow variation associated with an unstarted condition; engine compressor stalls; and miscellaneous events attributed to the air-induction control system and affecting the vehicle or engines. An example of the latter would be a rapid inadvertent opening of the main bypass doors resulting in a compressor stall. The majority of the unstart data points shown have been intentionally induced as part of the testing and development of the air-induction system.

As would be expected, most of the data points designating inlet events lie between Mach numbers 2 and 3, where most inlet testing has been done. The lower Mach number areas have been investigated in many previous airplanes and have not been the concern of the present program. Some of the data points may be grouped together into a series of related events which occurred sequentially during a single flight. For example, the events that are connected by the line were initiated when a piece of structure was ingested into the duct at Mach number 2.6 and an altitude of 62 000 feet, resulting in multiengine stalls, engine shutdown, unstart, and sustained buzz. The events extended over 6 minutes after which the vehicle was stabilized at Mach number 1.7 and an altitude of 45 000 feet. Inlet airflow interrelationships with engines and airplanes become important in the integrated XB-70 air-induction system as illustrated in figure 3. Shown are details of the left inlet airflow system. At cruise Mach number, about 81 percent of the airflow which enters the inlet is channeled as primary flow and actually enters the engines. About 16 percent is bled off by the extensive boundary-layer control system which rejects the undesired air in three ways. Boundary-layer plenums I and II reject air overboard directly behind the nose-wheel-well fairing, reducing the base drag in that region. Plenum IV air is rejected overboard through a fixed set of louvers. Plenum III air is channeled far aft into the engine region and is used for engine cooling or is rejected into the base region, reducing base drag. About 3 percent of the primary inlet air passes into the bypass plenum region through large perforations in the duct walls and is rejected through nozzles formed by the bypass doors in the upper wing surface or is ducted aft and used for engine cooling. The flow system exemplifies the sophistication required of the inlet to match airflow requirements of the engine, to remove boundary layer efficiently, and to reduce inlet drag.

The requirements for efficient shock-system control are illustrated in figure 4, a top schematic view of the left inlet. The vertical two-dimensional inlet achieves compression by means of a series of interacting oblique shock waves in the external and forward internal regions of the inlet duct, designating it a mixed compression inlet. The flow, reduced in Mach number by the shock system, traverses the inlet throat and becomes subsonic on passing through a normal shock. The strength of this normal shock, which is closely associated with the shock position, has a direct effect on performance of the inlet.

In order to maintain the desired shock system, a series of controlled movable ramps are positioned for optimum inlet performance. The bypass door areas are controlled to match the airflow requirements of the engines and to position the terminal shock by varying the duct back pressure. As the shock is positioned farther forward toward the throat, higher total-pressure recovery is achieved with resultant higher engine performance. However, a stability limit is approached at which the inlet may unstart. In some unstart cases, duct buzz may also occur. In either event, the performance of the inlet is reduced and, in addition, the effect of the inefficient and transient spillage of air may result in additional drag and require vehicle control inputs by the pilot. To avoid such events the inlet may be configured in a lower performance but more stable mode, with the shock farther downstream. When the inlet is started, the inlet throat height varies automatically with Mach number in accordance with a schedule which may be deviated to a low, intermediate, or high setting. The bypass-door control senses a pressure ratio in the throat region and controls the shock to a low, intermediate, or high performance setting which corresponds roughly to an aft, mid, or forward shock position. Many recent flights have been in the upper intermediate range and a few have been attempted at high performance. Some stabilized flight points are shown in figure 5 in relation to the unstart and restart boundaries experienced during wind-tunnel tests. The unstart margin is a function of both throat and bypass door settings. The unstart line shown in the figure is for throat-induced unstarts or the throat choking limit. These margins are being investigated in flight. The center line is the center of the intermediate flight operating range. The deviation of the points from the inlet throat schedule indicates the range of testing that has been conducted to explore the inlet flight envelope. Most of the points are well away from the unstarted region and reflect the general trade off which has been taken to insure stable operation. The degree to which this stability margin results in a reduction in inlet performance is illustrated in figure 6.

Shown are flight points of total-pressure recovery, primarily in the range for a started inlet. The main point to be drawn from these preliminary flight data points, achieved under essentially steady-state conditions, is that a wide range of performance is possible. In order to avoid inlet problems, a conservative approach was taken in the early developmental program by operating in the lower performance modes. These earlier flight points fall mostly below the shaded intermediate region. As flight experience is gained, higher performance points are being obtained.

At this interim point in the program it is not possible to state with confidence just what the maximum practical pressure recovery will be for cruise conditions. The predicted cruise goal is shown as a solid symbol in figure 6. (See ref. 1.) The data at the moment appear to be somewhat short of the predicted values, but it should be remembered that systematic tests to determine the inlet performance limits have not been accomplished. Furthermore, many of the systems of measurement on which inlet data depend are not as thoroughly calibrated and checked out as they will be later in the research phase of the program.

Finally, it should be noted that the flight data are taken only at engines 1 and 3, whereas the wind-tunnel data are taken at all three engine positions. (See refs. 2 to 4.) Quarter-scale wind-tunnel tests indicate higher pressure recoveries at the center engine position than at the other two. However, at a Mach number of 3 the differences are small and the correlation with flight is insufficient to permit an estimation of flight conditions for the center area with any degree of confidence.

The comparison between the wind-tunnel test and aircraft operating levels of recovery illustrates the importance of the inlet performance to stability trade off. Higher recovery has been achieved recently in flight in the high performance mode, but the time at Mach number 3 has been limited. These recent attempts to approach the better recovery at high settings have been accompanied by a greater incidence of unstart and some engine stalls. As these problems are resolved higher operational recoveries are anticipated.

Figure 7 presents another measure of inlet performance - distortion, which is defined as the difference between the highest and lowest total pressures at the engine compressor face divided by the average total pressure. Shown as shaded area is an envelope of distortions for the steady-state flight test points to date. Two typical flights are shown within the envelope. The distortion is, in general, low for high supersonic airplanes today which possibly accounts for the rather low incidence of compressor stall experienced with the XB-70 engines. The engine limit lines specified earlier in the program are shown for reference purposes. The presently used limit lines are defined by a different weighting method than shown here.

The general distortion trends suggest some areas for investigation. The high transonic peak may be associated with the initial inlet shock attachment point or the early bypass door movements. The bypass door schedule probably influences distortion and recovery in the region of the second peak above Mach number 2 when first controlling shock position. The distortion above Mach number 2 is influenced by such things as diffuser exit Mach number, boundary-layer interactions in the duct, and a diminishing bypass area as Mach number 3 is approached. These effects will be investigated in flight by a series of carefully controlled tests.

Most of the in-flight performance described in the previous figures had been predicted by the extensive series of wind-tunnel tests, but many of the installation and operational effects did not come forth until the inlet was incorporated into the full-scale flight vehicle.

Foreign-object damage (FOD), always a problem for air-breathing airplanes, has been unusually severe for the XB-70. FOD on such an inlet can become a more serious problem than just engine damage. An example was given earlier in which FOD triggered a series of events.

A different type of problem with foreign material was uncovered as a result of a recent flight to Mach number 3 at an altitude of approximately 70 000 feet in which both inlets unstarted. After the flight, the bleed holes in the boundary-layer removal areas on the throat ramps were found to be clogged. Apparently, compound used for polishing the inlet had filled portions of the porous surfaces containing bleed holes as small as three-hundredths of an inch. Resultant bleed flow blockage was a contributor to the instability of shock position which led to a double unstart at Mach number 3.

In spite of the fact that engine stalls have not been a problem with the XB-70, there is concern over the possibility of stalls in mixed compression inlets, particularly short inlets, because they can cause unstarts to occur.

Engine-induced stalls have not been as frequent as those caused by the inlet disturbances. Increased distortion as a result of an improper bypass door operation has been cited as the cause of stall in one case. Another more surprising stall occurred with the engine well within the stable operating region. It is suspected that noise associated with inlet duct internal turbulence as a result of a low performance inlet setting triggered the stall. Turbulence such as this is being investigated by the engine and airframe manufacturers to better understand and interpret the effects on the engine and its control system. Some spurious control signals have been experienced. The buzz indicator, which senses a pressure far downstream in the duct, is presently deactivated from the inlet control system. The reason is that during stable inlet operation the inlet cycled for a restart because the buzz sensor interpreted something incorrectly as inlet buzz. The control system commanded the large bypass doors to open in order to restart the supposedly buzzing inlet. Such bypass movements have produced effects on the vehicle nearly as pronounced as true unstarts. Restart cycles of the inlet control system have also happened when there were no unstarts. The cause of a series of spurious restart cycles was traced to a transient voltage which induced a signal to the inlet control system resulting in the restart cycle. Spurious control signals, whether aerodynamically, electrically, or mechanically induced, are a problem.

Of particular interest, are the effects of unstart and the corrective action of the inlet control system on the vehicle. Inlet unstart, and subsequent restart cycle, is as serious a problem to the control of the airplane as it is to the performance of the inlet. In figure 8 is shown a double unstart that occurred during a turn at Mach number 3. The left duct unstarted 2 seconds after the start of the time history and the right duct unstarted 11 seconds later. The change in pressures under the left wing caused by the expulsion of the normal shock forward of the inlet lip combines with the opening of the bypass doors, which act essentially as elevons, to produce an increase in the normal acceleration. The pilot counters this pitching motion with a longitudinal control input of approximately 3° nose-down elevon. Without this input the airplane would have pitched to a higher load factor. Likewise, loss of thrust, increased spillage drag, and the opening of the bypass during the restart cycle caused a longitudinal deceleration of approximately 0.1g. Perhaps even more significant than the steady-state deceleration is its rate of onset, or jerk, which is very nearly a 0.1g step function. The unstart and door movements also affect the lateral control of the airplane causing it to roll toward the side that has unstarted. The pilot's corrective action prevents the roll rate from becoming large but there is a noticeable change in bank angle. There have been a number of false unstarts with similar effects on the airplane. It has been suggested that this unstart was caused by foreign material in the boundary-layer bleed holes but recent experiences with additional double unstarts at Mach numbers from 2.7 to 3.0 have shown this to be only a partial answer.

CONCLUDING REMARKS

The XB-70 air-induction system is generally satisfactory, is adequately matched to the engine flow requirements, and can be controlled for the various flight ranges. The large size of the duct and the arrangement of the engines probably contribute to the unusual amount of foreign-object damage experienced. Flow distortion at the compressor face is well within the permissible range and has been insufficient to cause engine performance loss at most flight conditions. Inlet unstarts at cruise Mach number constitute a new problem for high supersonic aircraft seriously affecting the dynamics of the inlet and airframe. The noise, like a muffled explosion, and the aircraft gyrations are unacceptable for pilot and crew.

The allowable in-flight margins between inlet stability and optimum performance in flight including effects of turbulence, passing shocks, and other disturbances will be evaluated and compared with wind-tunnel experience, theoretical predictions, and computer simulations in a joint NASA/USAF XB-70 program.

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XB-70 IN FLIGHT

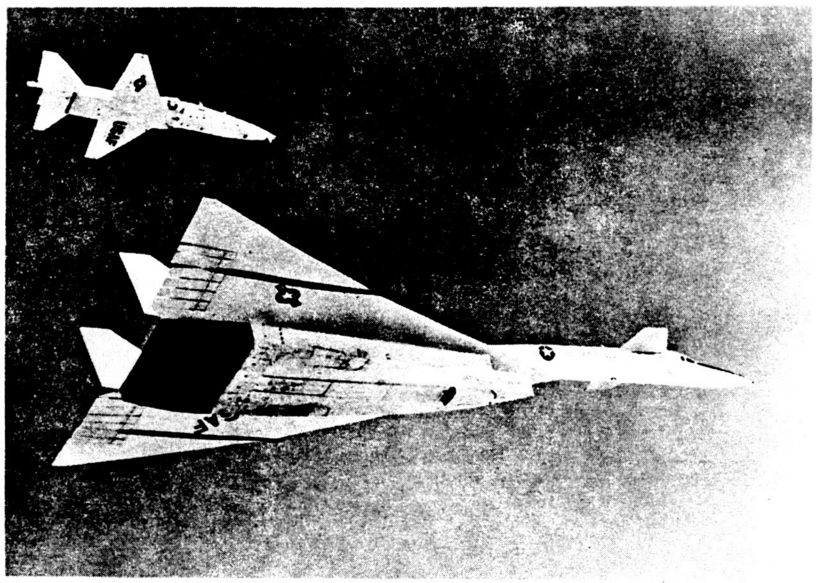

Figure 1

AIR-INDUCTION-SYSTEM EVENTS

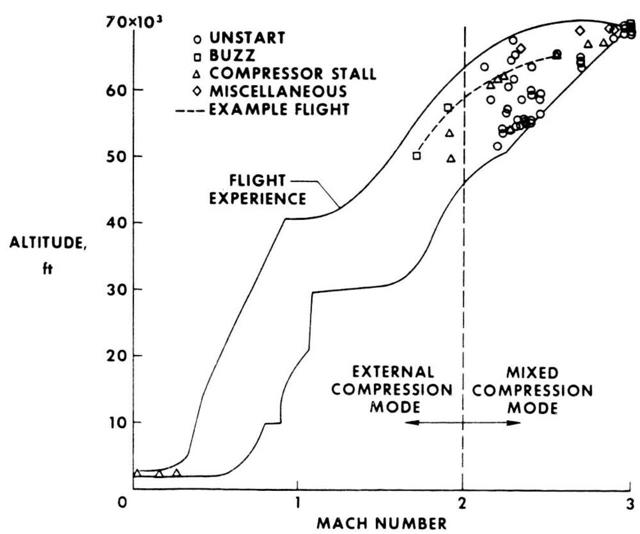

Figure 2

AIRFLOW SYSTEM
LEFT INLET

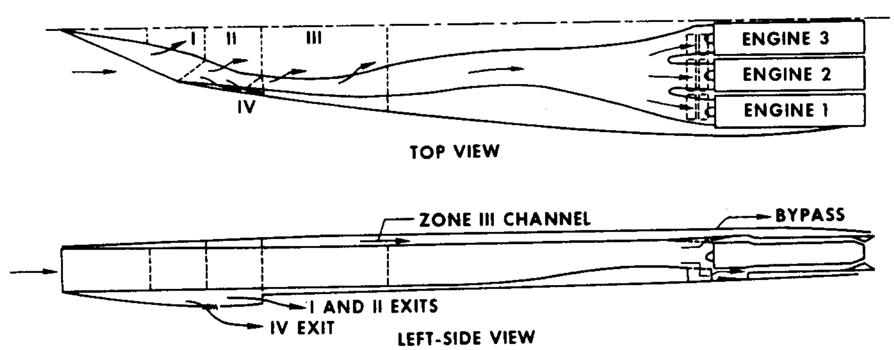

Figure 3

XB-70 INLET SCHEMATIC
TOP VIEW, LEFT SIDE

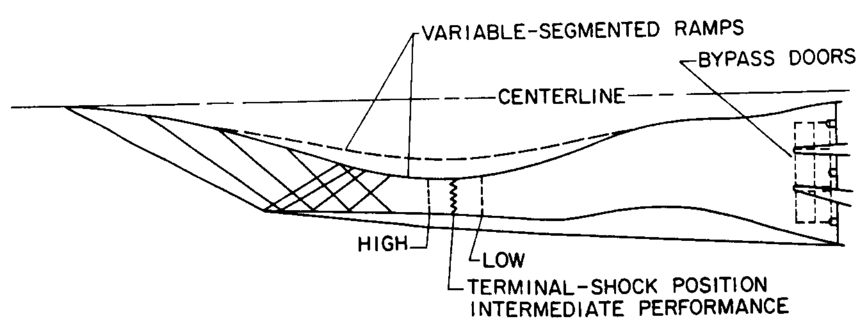

Figure 4

INLET OPERATING REGIONS

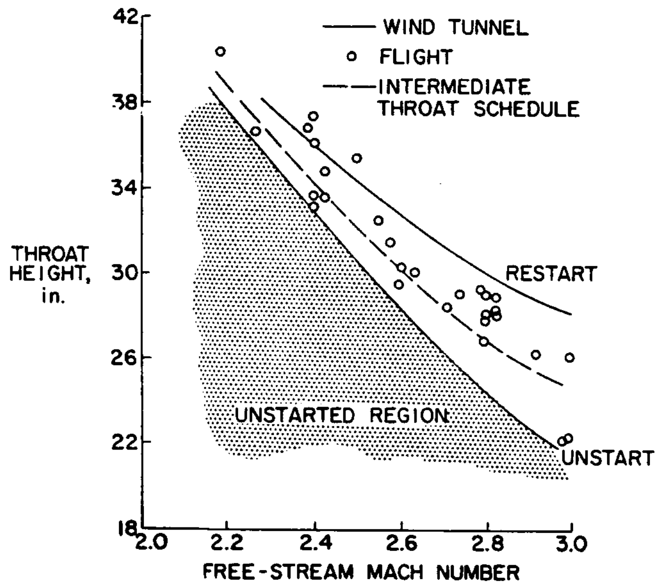

Figure 5

TOTAL-PRESSURE RECOVERY AS A FUNCTION OF MACH NUMBER

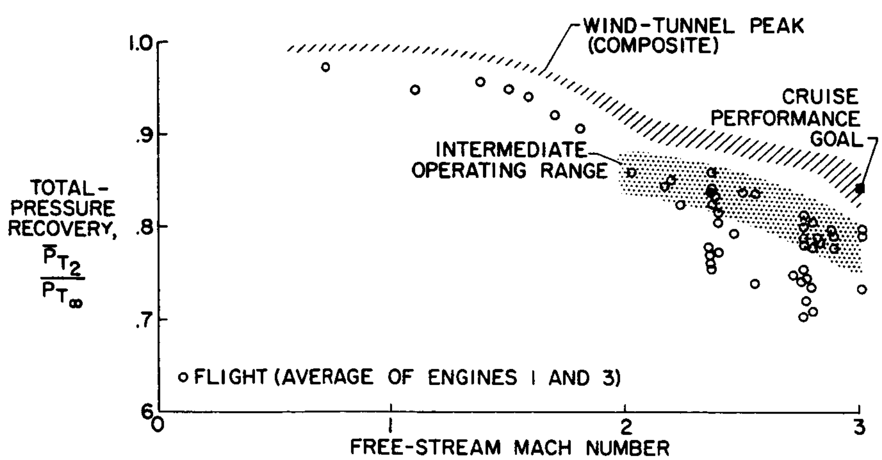

Figure 6

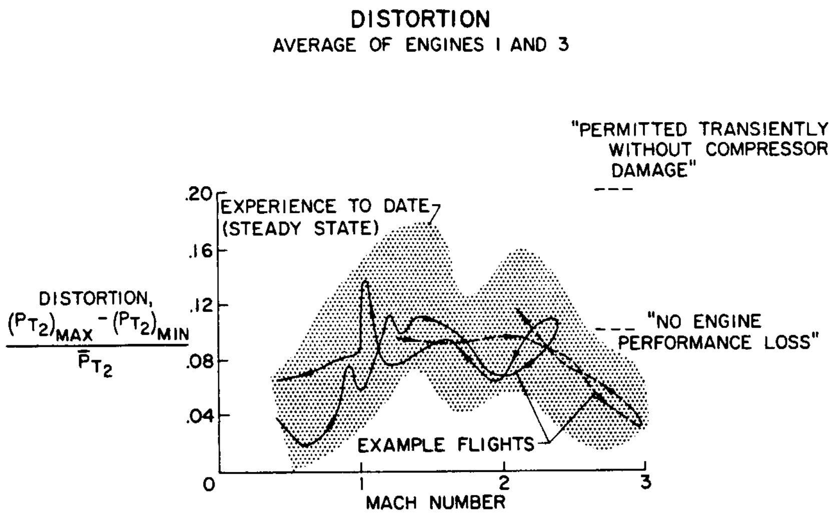

Figure 7

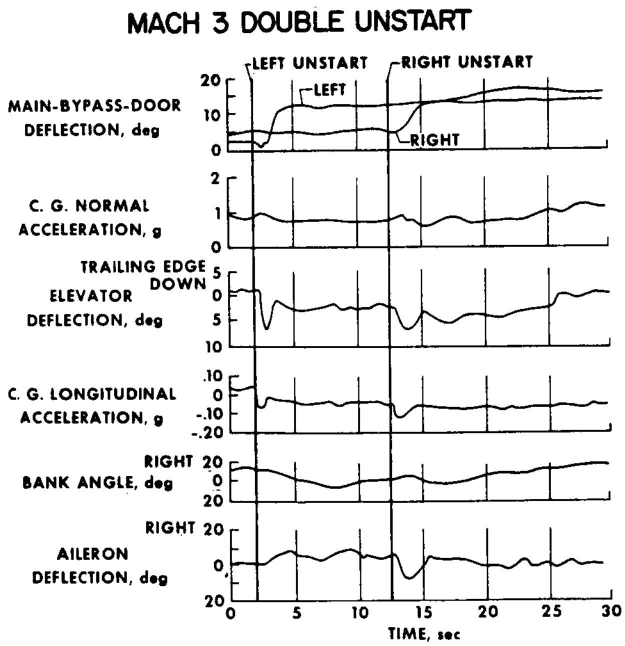

Figure 8