Results of a Preliminary Investigation of Inlet Unstart on a High-Speed Civil Transport Airplane Concept

Christopher S. Domack
Lockheed Engineering & Sciences Co.
Langley Program Office
Hampton, VA 23666

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Introduction

The aircraft design engineer today is tasked with satisfying an increasing number of conflicting requirements.The fact that conflict in these requirements may be technically, economically, or politically motivated usually compounds the difficulty of determining the best solution to a design issue. In this regard, propulsion/airframe integration for supersonic airplanes must rank as one of the most challenging aspects of airplane design.

For the cruise Mach numbers currently being considered for High-Speed Civil Transport (HSCT) airplanes, the inlet requirements of low drag, low bleed flow, and high pressure recovery appear to be best met with a mixed-compression design. Unfortunately, these desirable attributes come with a highly undesirable companion: the inlet unstart phenomenon. Concern over the effects of a mixed-compression inlet unstart on the vehicle dynamics of large, high-speed aircraft is not new; a comprehensive wind-tunnel study addressing the problem (ref. 1) was published in 1962. Additional investigations of the problem were made throughout the United States SST program and the follow-on NASA programs into the late 1970's. The current study sought to examine the magnitude of the problem in order to determine if an inlet unstart posed a potential hazard severe enough to preclude the use of mixed-compression inlets on proposed HSCT concepts.

HSR '91 Inlet Unstart Analysis

Supersonic commercial airplane inlet unstart susceptibility is not a new concern

- o NASA off-design mass flow test (1962)
- o NASA inlet isolation concepts (1966)
- o Boeing analytical studies (1969, 1976)
- o Lockheed wind-tunnel tests (1976)

The Inlet Unstart Phenomenon

The term *unstart* refers to the expulsion of the shock system internal to the cowl in a mixed-compression or internal-compression inlet. An abrupt change in operating conditions (e.g., wind shear or large freestream temperature change) may cause an unstart. During an unstart, the inlet mass flow is drastically reduced, and its drag is greatly increased. Due to the abrupt mass flow reduction and increase in inlet flow distortion, the affected engine's compressor may stall and its combustor flame out. An unstart may also be *caused by* a compressor stall upon a sudden change in engine airflow demand such as afterburner ignition. Inlets with increasing amounts of internal compression, more desirable as cruise Mach number increases, tend to be less tolerant of operating disturbances. Some experimental evidence reported in reference 2 suggests that an axisymmetric inlet configuration may exhibit greater angle of attack tolerance than an equivalent two-dimensional configuration.

The shock wave that propagates upstream during a compressor stall is termed a *hammershock.* Once a compressor stall has commenced, the expulsion of the hammershock takes place in milliseconds. Figure 1, from reference 3, indicates that the static pressure at the engine compressor face produced by a hammershock may be more than twice the static pressure in the inlet during normal operation, and that the strength of the hammershock is directly proportional to the compressor system static pressure ratio. A particularly strong hammershock may cause damage to the inlet structure and precipitate engine damage.

Comparison of Hammershock Pressure Ratios for Several Engines

Ref.: NASA TM X-71594

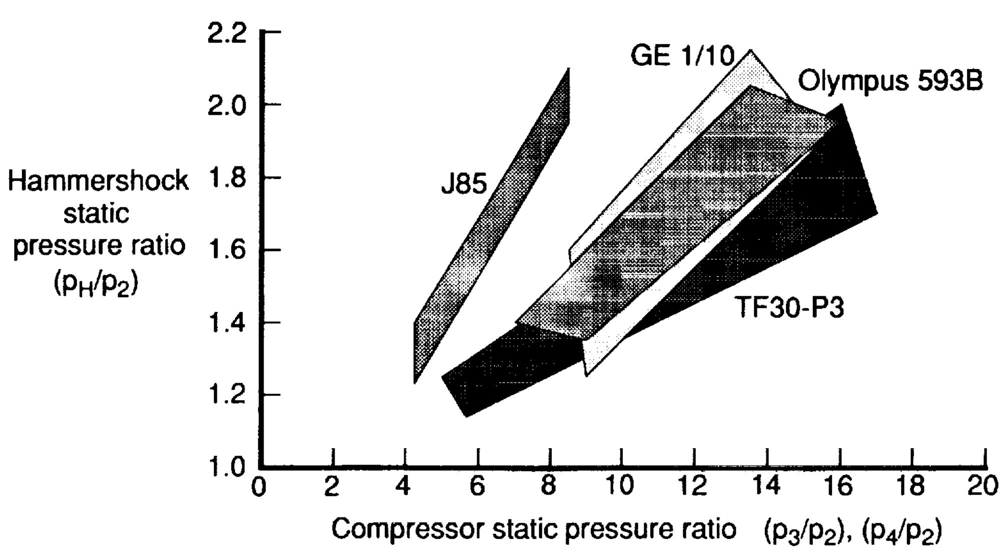


Figure 1.

An inlet unstart has effects on an aircraft besides engine operation. As illustrated in figure 2, from reference 4, the flow upstream of an unstarted inlet may interact with the boundary layer on adjacent surfaces. If the affected boundary layer happens to be on a wing or other airframe component with flight control surfaces, the potential exists for degradation of control surface effectiveness and increased drag due to shock-induced boundary layer thickening or separation. Ingestion of the thickened boundary layer by the engine could also affect engine operation and make a restart more difficult. The bow shock of an unstarted inlet may impinge on adjacent engine inlets and cause them to unstart also.

The asymmetrical changes in the engine thrust, inlet drag, and nacelle pressure field beneath the wing for "conventional" HSCT configurations could cause the airplane to pitch, roll, and yaw. The loss of thrust and increase in drag would also result in an abrupt deceleration. Several methods, both passive and active, have been proposed to minimize these vehicle dynamic effects. Passive approaches seek to reduce the effects of an inlet unstart through judicious nacelle placement and the use of fixed aerodynamic devices to prevent unstart propagation. Active approaches involve minimizing the asymmetry of the flight condition through the use of automatic engine and flight controls. The required level of control automation appears to be well within the current state of the art.

Shock/Boundary Layer Interaction due to Inlet Unstart

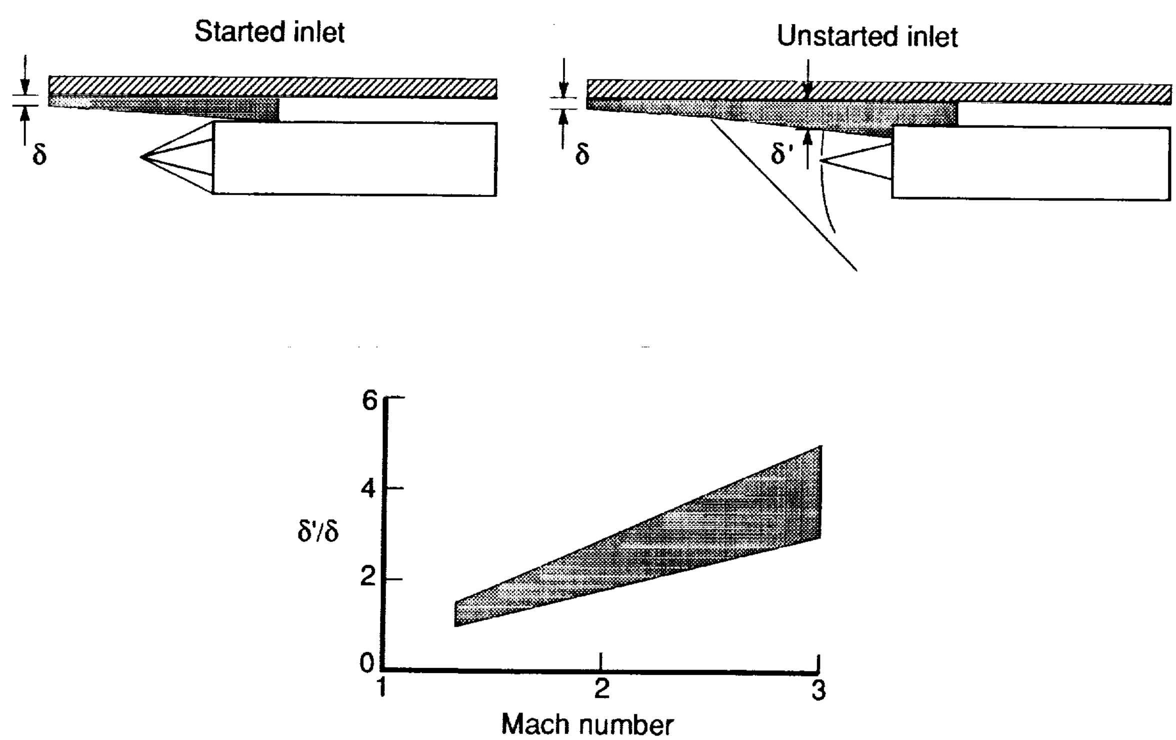


Figure 2.

Figure 3, also drawn from reference 4, shows the nacelle spacing requirements for a pair of axisymmetric, Mach 3, mixed-compression inlets to prevent an unstart on one inlet from unstarting the other. The unstarted inlet in this case was in a steady-state buzz condition. The author of this reference cautioned that these data should be viewed with reservation for design purposes, as they may depend on the degree of shock/boundary layer interaction present and on the operating characteristics of the inlets under consideration. Conservatism would dictate somewhat greater spacing requirements than those shown in the figure.

The difficulty in predicting the occurance of mutual unstarts and the susceptibility of a given inlet configuration to the problem is substantial. Contrary to what might be expected, it was also noted in reference 4 that an unstart in one branch of the bifurcated inlet of the XB-70 airplane did not generally induce an unstart on the other side. This characteristic was thought to be at least partly attributable to the inlet configuration of the XB-70, a vertical wedge mounted beneath a large boundary layer separation plate.

Nacelle Separation Requirements

M=3, mixed-compression, axisymmetric inlets; steady-state buzz

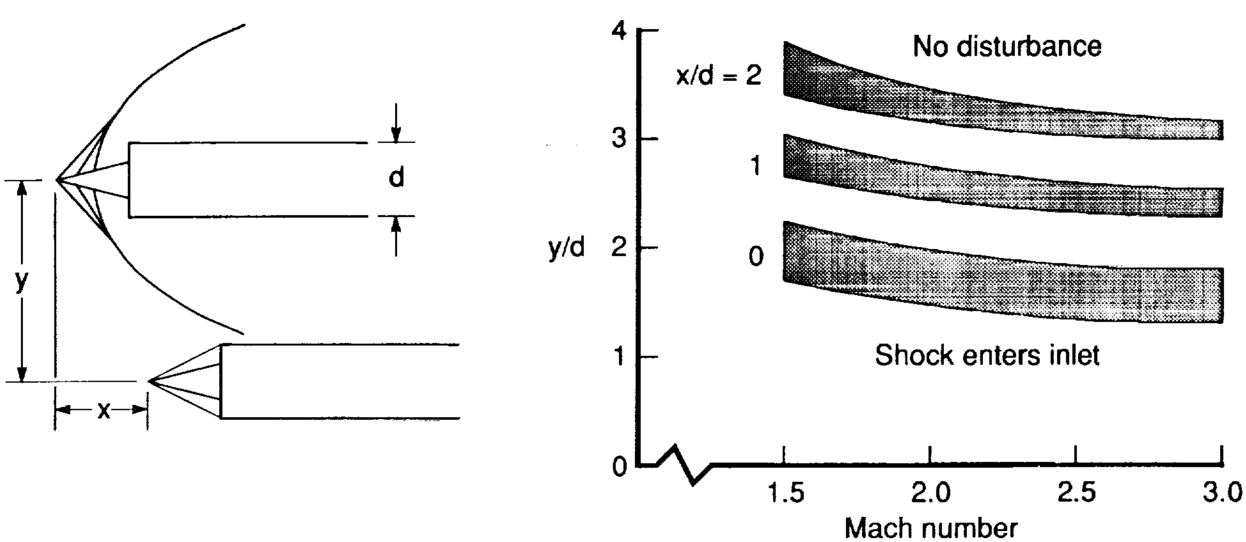


Figure 3.

Another passive concept that has been tested successfully (ref. 5) in the prevention of mutual unstarts is the splitter plate. Figure 4 is an artist's concept of a splitter plate installed on a twin-engine nacelle to isolate one inlet duct from the other. It was reported in reference 5 that splitter plates of practical size will isolate an unstarted inlet at Mach 2.5 if the mass flow ratio of the unstarted inlet is maintained above about 0.65. The plates remained effective for yaw angles up to 6 degrees windward. For nacelle installations close to the wing undersurface (low mounting pylon heights), it was found necessary to eliminate any gap between the splitter plate and the wing. Splitter plates have also been proposed for installation between axisymmetric, individually-podded engines (ref. 6) to prevent propagation of unstarts. The required size and effectiveness of such an installation is not known.

Active control systems have been implemented on the SR-71 and Concorde aircraft to minimize vehicle accelerations and displacement angles. The SR-71 inlet control system incorporates what is called a *crosstie*; upon detection of an inlet unstart on one side of the aircraft *both* inlets immediately begin a restart cycle, thus avoiding a large lateral-directional force asymmetry. A similar philosophy was proposed by Boeing in a 1977 supersonic transport configuration study (ref. 7.) A prototype digital integrated airframe/propulsion control system was successfully tested (ref. 8) as a replacement for the original analog systems on the SR-71 in 1979. The Concorde's air intake control system, described in reference 9, is linked to an autorudder control in order to prevent the development of unacceptably large sideslip angles upon detection of an engine or intake malfunction.

Inlet Splitter Plate Concept

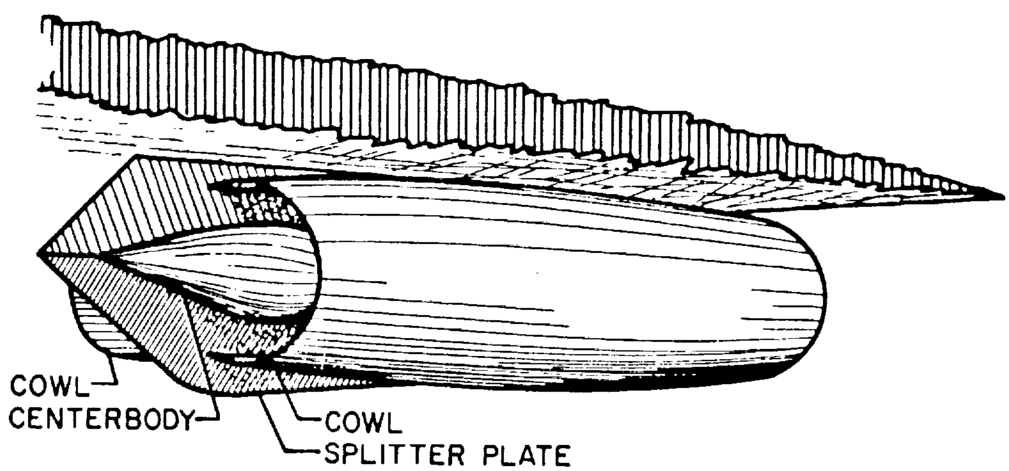


Figure 4.

Inlet Unstart Effects on an HSCT Concept

Reference 6 also provided data upon which a simple kinematic analysis of inlet unstart effects on an HSCT vehicle concept was based. These data, summarized in figure 5, consisted of wind-tunnel test results for an aircraft configuration very similar to those currently under consideration, but with three different nacelle locations. Each of the nacelle locations was tested at three different inlet mass flow ratios, accomplished by varying the amount of internal blockage in the model nacelle. Area blockages of 0%(free-flowing), 50% and 100%(no flow through) were tested.

Wind-tunnel Test Data Summary

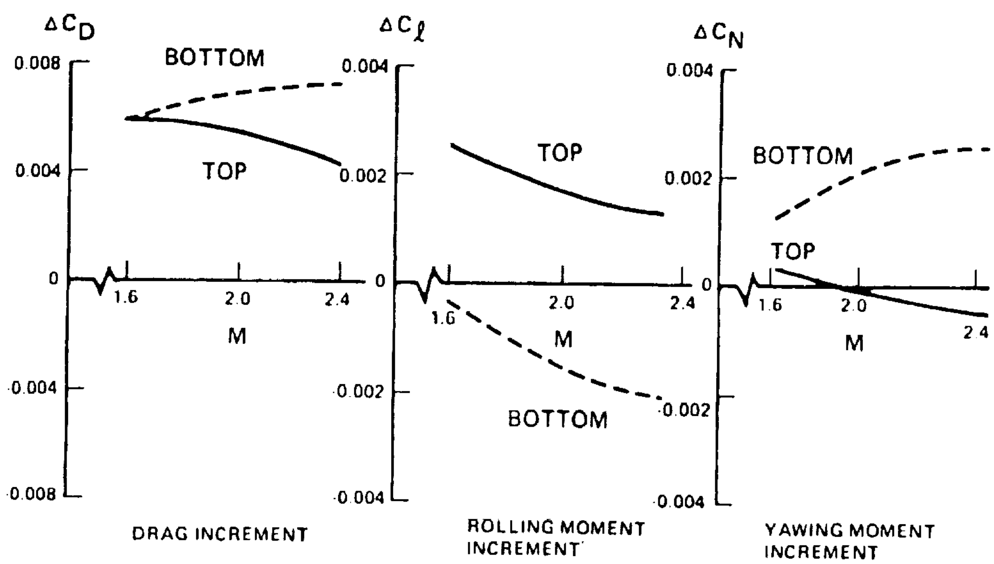
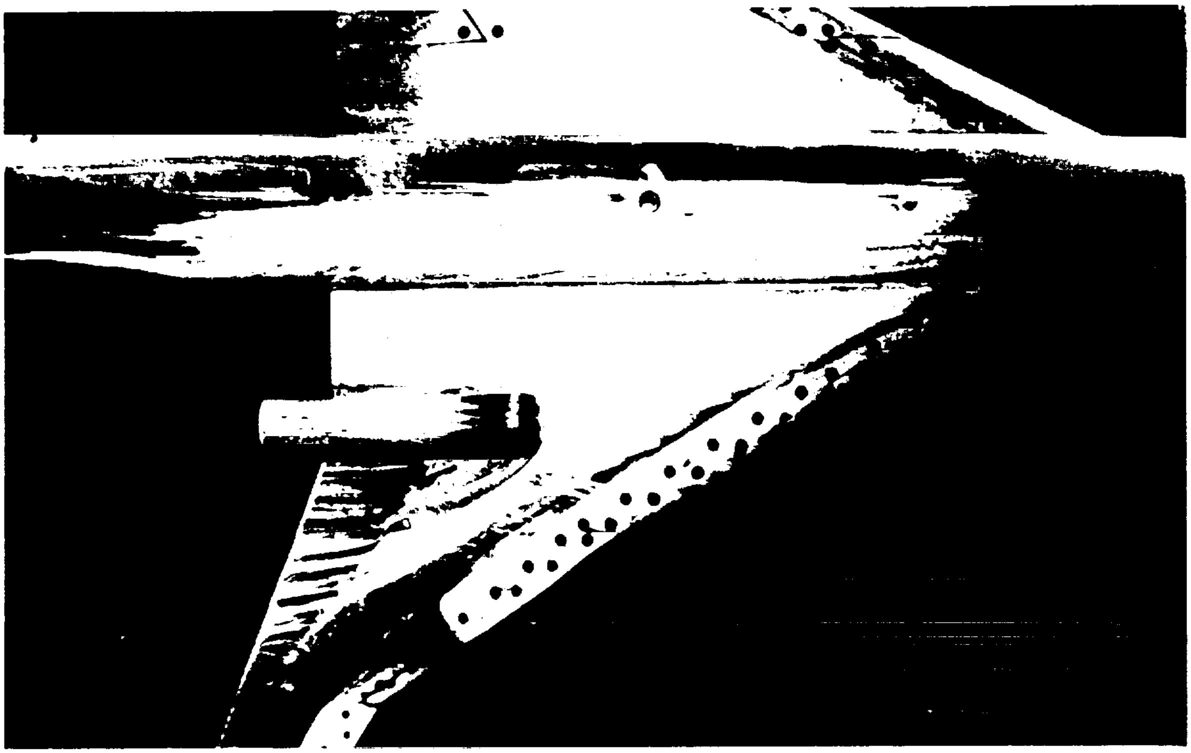


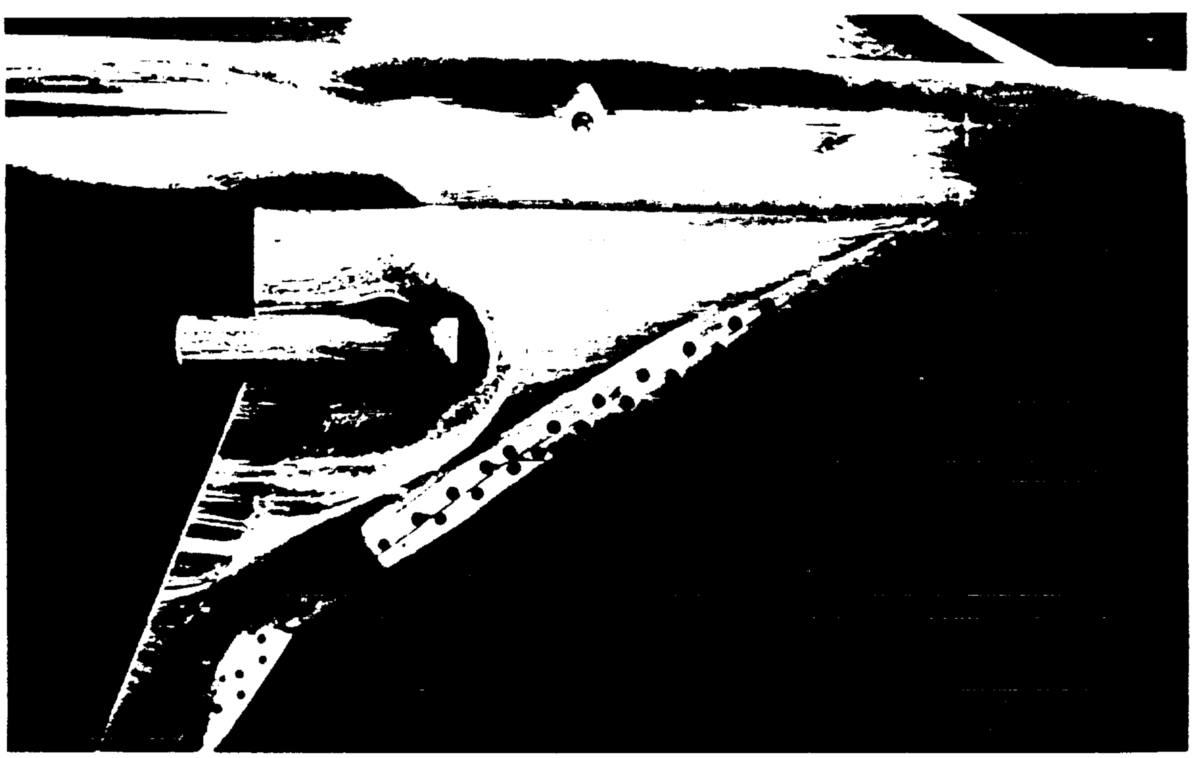
Figure 5.

Figure 6 illustrates the results of oil flow studies done during the Lockheed wind-tunnel test; the effect of the simulated unstarted inlet (50% blocked nacelle) on the wing streamlines is substantial and clearly evident. The photographs were taken at a test Mach number of 1.6 and an angle of attack of two degrees. Though the photographs show nacelle N1, which was the inboard nacelle mounted on the upper surface of the wing, similar results would be expected for nacelles mounted beneath the wing. One of the conclusions stated in reference 6 was that, based on these data, the over/under nacelle installation of the Lockheed concept posed less of a problem upon inlet unstart than a conventional four-engine underwing installation.

M = 1.60 α = 0.0349 RAD (2.0°)



N_1 FREE FLOWING



N_1 50 PERCENT BLOCKED

Figure 6.

The following assumptions were made in the kinematic analysis in addition to the use of the wind-tunnel data just described. For conservatism, and since the analysis was for an instantaneous (peak) condition rather than a sustained, steady-state condition, the drag force of the hammershock pressure pulse acting over the assumed inlet capture area was included and only rigid airplane motion was considered. Additionally, the snapshot analysis does not include forces and moments opposing the unstart that would be generated by the basic airframe aerodynamics or flight control system.

Assumptions

- o Sample configuration as per CR-145133
- o Engine-out condition initiated at M=2.0, h=55000 ft, n=1.0
- o Outboard engine, locked rotor
- o Inboard engine, inlet unstarted
- o Roll, pitch, and yaw inertias from NASA AST-105 configuration
- o Wind-tunnel data from Lockheed test (underwing nacelles only)
- o Seized engine taken as 100% blocked condition
- o Unstarted engine taken as 50% blocked condition
- o Thrust of failed engines zero; cruise thrust (12,500 lb) on others
- o Hammershock pressure pulse included in drag force
- o Instantaneous accelerations and angular rates only
- o Rigid-airplane motion only
- o No opposing propulsive or aerodynamic control forces

The free-body diagram presented in figure 7 was used in the kinematic analysis. Dimensions shown are generally representative of a Mach 2.5, 290-passenger vehicle with a gross weight of 600,000 lb as described in reference 6. The accelerations were analyzed at the crew station because it was the point furthest from the airplane center of gravity, about which the angular acceleration rates were calculated.

Inlet Unstart Analysis Force Arrangement

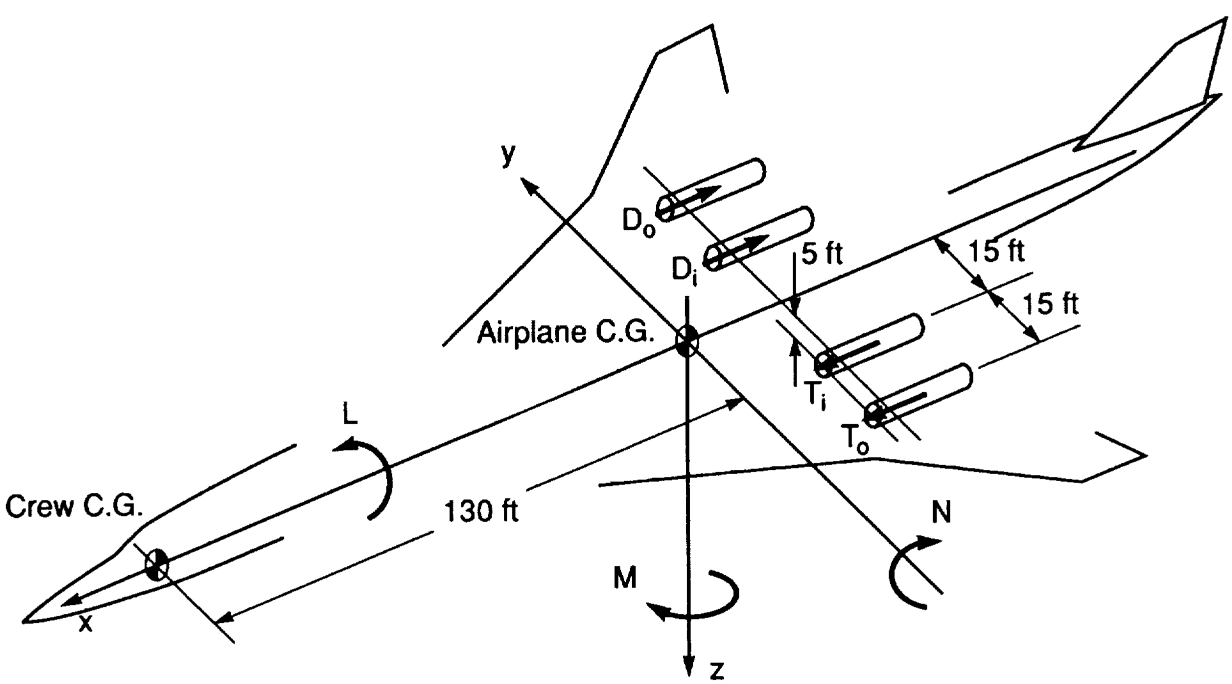


Figure 7.

Results of the analysis are shown in the accompanying table below. Even with the substantial level of conservatism in the analysis, the acceleration levels at the crew station are seen to be relatively mild. The instantaneous acceleration rates at cabin locations closer to the airplane center of gravity would be even lower. The accelerations calculated are of the same order of magnitude as those experienced in light to moderate turbulence in a modern subsonic transport, or in an automobile on a rough road.

In short, although the forces on the airplane during an unstart are large, so is its inertia. Therefore, *unless the unstart forces are sustained and unopposed* by the pilot, flight control system, engine controls, or combinations thereof, large rates and angular displacements are unlikely to develop. The potential for passenger injury due to vehicle motions induced by an unstart thus appears no more serious than that due to normal atmospheric turbulence. There is, however, a passenger-related aspect to the unstart problem that may require further investigation. It is likely that the noise of an inlet unstart (probably like a muffled explosion) would be very distressing to passengers, and attempts should be made to explore the magnitude of this problem.

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Results

Axis	Cockpit accel, g	Angular accel, deg/s^2
Roll	-.04	15.1
Pitch	-.04	0.5
Yaw	.24	3.3

- o Although the forces involved are large, so are the airplane inertias; thus the resulting accelerations are small
- o The instantaneous rates represent a worst-case (peak) situation; steady-state values will be lower

Validation of Results

With the tabulated values in hand, an attempt was made to find flight data to test the validity of the calculated accelerations. Figure 8, from reference 10, shows the lateral and longitudinal responses of the Concorde aircraft to a double engine surge. Recall that the automatic flight control system of the airplane immediately applies corrective rudder input upon sensing an asymmetrical thrust condition; this can be seen clearly in the recording of rudder angle. The aircraft stabilizes in about 12 seconds at very small angles of bank and sideslip, and decelerates smoothly at constant altitude. The control surface deflections required to contain the transient are quite small.

The double engine surge condition is presented for the Concorde because it is the practical equivalent of a double unstart as described for the conceptual HSCT. The Concorde inlets do not "unstart" in the strict sense of the word, because they are basically an external-compression design. However, like other external-compression inlets, they are susceptible to the *buzz* instability, and incorporate active control measures similar to those required for mixed-compression inlets.

Concorde Response to Double Engine Surge

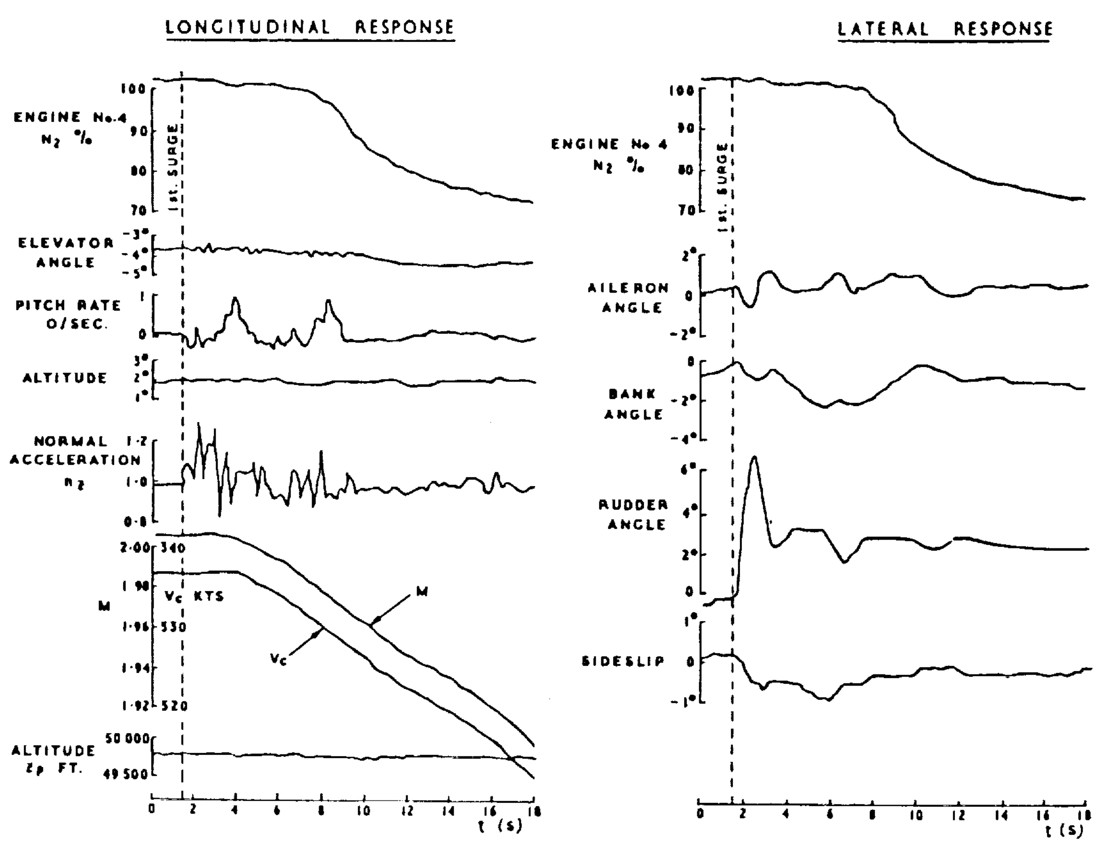

Figure 8.

A similar flight test history was found in reference 11 for the XB-70 airplane, and is presented in figure 9. The reactions to a double unstart in this case are somewhat more pronounced than those of the Concorde; however, recall that the XB-70 traces shown are for Mach 3 as compared to Concorde's Mach 2 cruise. A pilot's description of an XB-70 unstart transient was published in reference 12. The unstart transient was termed "mild," with about 25% of the available roll control power being used to counter the induced rolling motion. The comment was also made that even though most XB-70 inlet unstarts were deliberate, each unstart event was startling even to a crew experienced in flight testing.

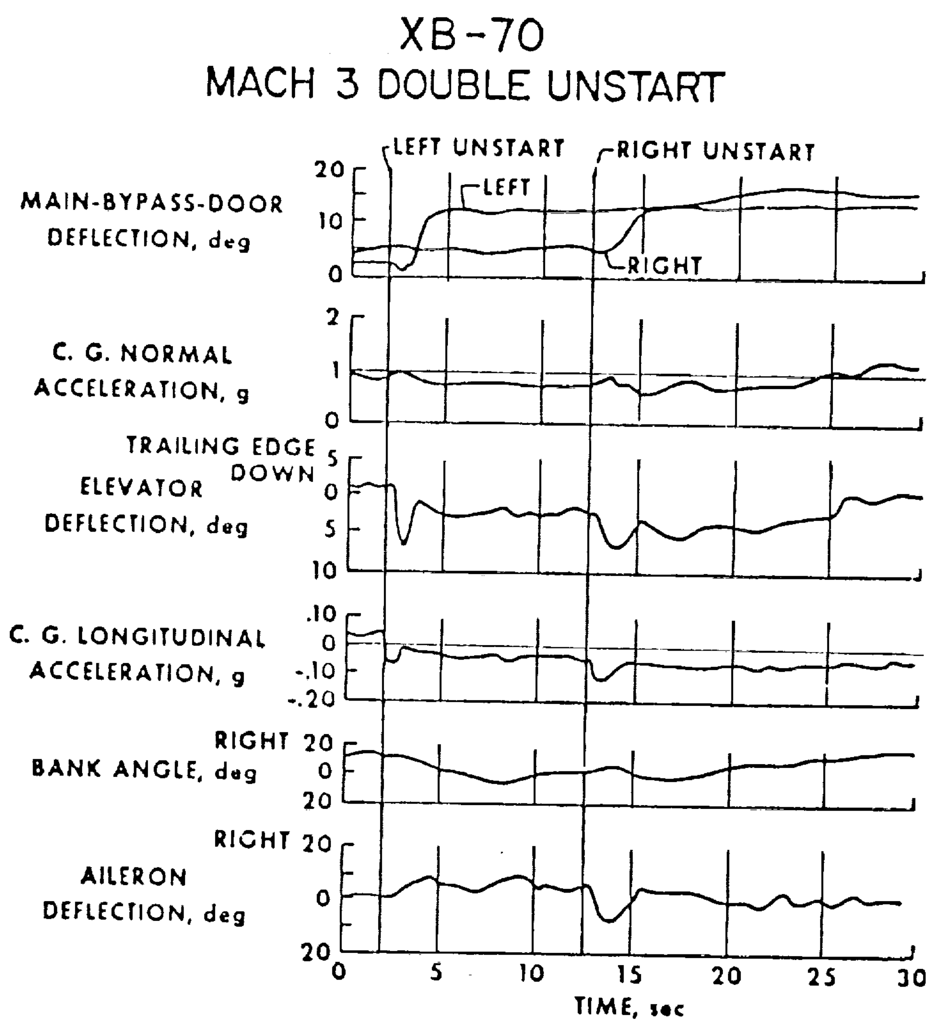

Figure 9.

Considerable attention has been devoted in popular aviation literature to the inlet unstart behavior exhibited by the YF-12 / SR-71 airplane. Colorful metaphors and dire predictions of helmets slamming into cockpit windows make entertaining reading; an engineering assessment of the problem is more mundane (fig. 10.) While the unstart effects on this airplane are certainly more severe than those shown previously, it is most important to realize why this is so, and why an extrapolation of these results to an HSCT is not valid.

Undoubtedly, the unstart problems experienced by the YF-12 airplane in its development phase were severe, and the source of many of the aforementioned pilot comments. The results shown in figure 10 were obtained with the production stability augmentation system and automatic inlet control system operating, and still show significant accelerations and displacements of the airplane caused by the unstart; note that recovery from the condition used up over half the available lateral-directional control power. This behavior is largely the result of configuration attributes which are unlikely to be shared by an HSCT airplane. For example, the relative size (thrust) and placement of the YF-12 powerplants are very different from the four-engine underwing installations proposed for most HSCT airplanes. The YF-12 nacelle itself contibutes to some stability and control problems due to the design and operation of the various bypass and bleed provisions; reference 13 contains a description of some of these effects. The higher thrust-weight ratio, higher cruise altitude and Mach number, and lower cruise lift-drag ratio of the YF-12 / SR-71 compared to current HSCT concepts are also important differences influencing the airplane's response.

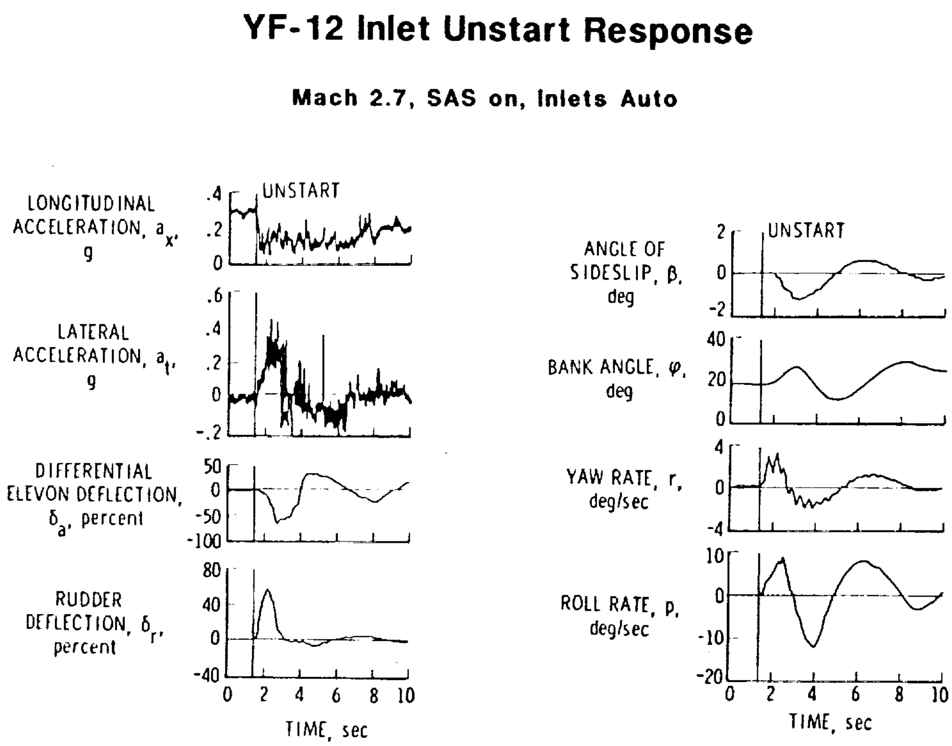

Figure 10.

Conclusions and Recommendations

The points listed in the table below are largely self-explanatory, but require some additional comment. Most importantly, the results of this study of the inlet unstart problem indicate that the mixed-compression inlet unstart is *not* a severe enough problem, *from a passenger safety standpoint,* to prohibit their consideration for current HSCT concepts. However, it would be desirable to examine the unstart problem further through more sophisticated analyses in order to develop a better understanding of the design drivers behind the vehicle effects. A design methodology could then be developed which would permit rapid screening and evaluation of inlet/airframe configurations with regard to inlet unstart susceptibility and effects. A large question concerning passenger acceptance of the startle upon an unstart still remains, and should be addressed through appropriate studies.

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Conclusions and recommendations

- o Inlet unstart on HSCT is an important design concern
- o Unstart is not likely to be a Mach number selection driver
- o Unstart does not appear to be a critical flight safety issue hindering HSCT development or operation
- o The automatic engine management and flight controls on an HSCT would minimize airplane motions; however, passenger startle may be a more difficult problem
- o Other flight conditions should be examined
- o More sophisticated studies are probably warranted

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