50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition
09 - 12 January 2012, Nashville, Tennessee

AIAA 2012-0013

An Overview of Military Aircraft Supersonic Inlet Aerodynamics

Dr. Richard K Scharnhorst[1]
The Boeing Company, St. Louis, MO, 63166

While the aerodynamics of inlets for supersonic military aircraft has not changed over the years, our understanding and ability to exploit it has. Since the advent of supersonic manned flight in the late-1940's, inlets have evolved to enable higher Mach-number flight with increasingly more complex designs and features. Two of the more note-worthy that represent this evolution as well as the main supersonic aerodynamics are the F-15 inlet system and the Diverterless Supersonic Inlet on the F-35. However, these designs and others all address the same aerodynamics of: oblique shock-wave boundary-layer interactions, normal shock-wave boundary-layer interactions, cowl/inlet lip shaping, inlet spill drag, and flow control. All of these are fruitful areas for continued research and investment.

Nomenclature

a	=	Speed of sound [ft/s]
A_c	=	Inlet Capture Area [ft^2]
CFD	=	Computational Fliud Dynamics
DSI	=	Diverterless Supersonic Inlet
g_c	=	Gravitational constant (32.174 ft/s^2)
M	=	Mach Number
m-dot	=	Mass flow rate [lb/s]
NSBLI	=	Normal Shock-Wave Boundary Layer Interaction
OSBLI	=	Oblique Shock-Wave Boundary Layer Interaction
P_{t0}	=	Freestream Total Pressure [psia]
T_{t0}	=	Freestream Total Temperature [^oR]
WTAP	=	Mass-Flow Function

I. Introduction

Since the advent of manned flight well over a hundred years ago, man has sought to go faster and higher to escape the shackles of earth. The development of the jet engine has ushered in a new era in the pursuit of this quest and has enabled man to break the sound barrier. A key enabler in this on-going journey has been the continued evolution of supersonic inlets to provide high quality airflow to this "new" source of propulsive power.

Over the years, supersonic inlets have been developed, designed, built, tested, failed, succeeded, moved, bled, swept, twisted, and adapted to meet ever more challenging requirements and speed regimes. This paper offers a brief history of supersonic inlets over recent years and highlights some of the interesting and increasing aerodynamic challenges that have been met in yesterday's and today's military aircraft. The review starts with the Bell X-1 and covers various supersonic aircraft including the F-4, F-15, F/A-18, F-22, B-1, and others. Various features are pointed out and future areas of study are suggested to nurture the further evolution of supersonic inlets for military aircraft.

A. Supersonic Military Aircraft

To understand the aerodynamics of supersonic inlets on military aircraft, it is imperative to understand the aircraft purpose and use. For example, fighter aircraft are often geared for supersonic dash to reach areas of potential conflict quickly, yet still operate and maneuver efficiently at subsonic speeds. Supersonic bombers on the other hand

---

[1] Associate Technical Fellow; Propulsion, Configuration Design and Weights; P. O. Box 516, St. Louis, MO 63166; M/C S064-2412; and AIAA Senior Fellow.

are designed to cruise efficiently over long distances at high speeds in order to deliver large payloads in a timely manner. Fighter/attack/bomber aircraft are designed for a blend of these missions and present their own unique supersonic inlet design challenges, as do aircraft that are launched from and recovered on aircraft carriers.

The first supersonic, manned aircraft was the Bell X-1 piloted by retired Maj. Gen. Charles "Chuck" Yeager. He was the first to *officially*[2] break the sound barrier on October 14, 1947. However, it was a rocket-powered plane and did not have an inlet. The first operational, manned, supersonic, jet-engine-powered aircraft was the F-86 "Sabrejet" built by North American Aviation and first flown on October 1, 1947. It featured a nose, normal-shock or "pitot" inlet. As illustrated in Figure 1, more and more aircraft have been developed since that time that were able to achieve higher and higher speeds as technology advanced and supersonic inlet aerodynamics were better understood. These aircraft were developed mainly in the military arena where funding by governments fueled technology advancement.

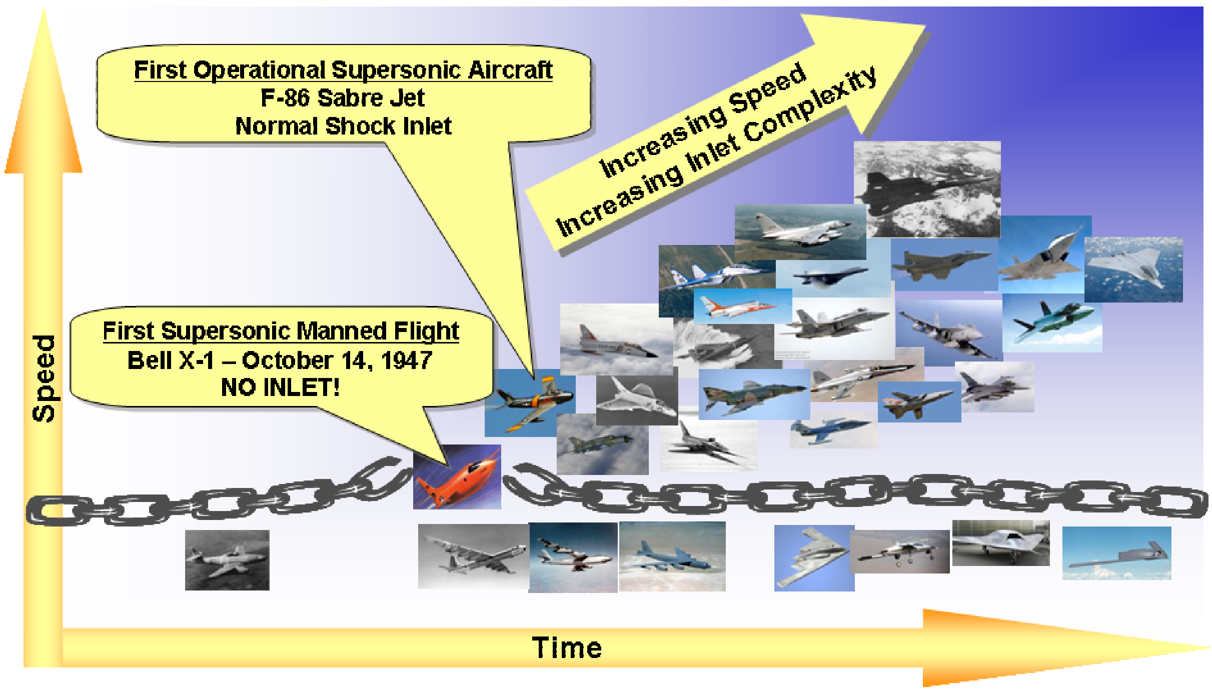


Figure 1 – Military Aircraft Over The Years

A few of the more notable were the F-4 Phantom; the F-15 Eagle; the F-16 Falcon; the F/A-18 C/D Hornet and E/F Super Hornet; the F-22 Raptor; the B-1 Lancer Bomber; and the more recent F-35 Lightning II. There was even a supersonic aircraft which took off and landed on the water called the Convair F2Y "Sea Dart". There are several videos documenting flights of this aircraft on the internet. A host of others were developed outside the US and included the MiG series developed and built by the former Soviet Union; the Pavania Tornado GR4 developed jointly by the United Kingdom, West Germany, and Italy; and the Eurofighter Typhoon developed by a consortium of companies (EADS, Alenia Aeronautica, and BAE Systems). All these aircraft are supersonic military aircraft, albeit with different missions and capabilities, but all with inlets designed for these missions and capabilities. As illustrated in Figure 1, capability, and often with it complexity, has increased as need has evolved over time. Nonetheless, there are common features and flow physics in all of them that have become better understood through research, study, and investment.

B. Supersonic Inlet Design Considerations

While the focus of this paper is aerodynamics of supersonic inlets, it is important to understand that this is not the only area to consider for the military aircraft inlet designer. Requirements fall generally into three broad

[2] Others claim that North American test pilot George Welch unofficially broke the sound barrier during a dive with the XP-86 on October 1, 1947; Wagner, Ray. *The North American Sabre*. London: Macdonald, 1963.

categories. They are: (1) Mechanical, (2) Environmental, and (3) Aerodynamic. All these categories were addressed in development tasks for the F-22 inlet (Ref. 1). Within the Mechanical category, supersonic inlets should be simple for reliability. The fewer moving parts they are, the less likely failure will occur. They should also be serviceable in order to maintain high sortie rates and facilitate easy field repair if required. Supersonic inlets (or any inlet system for that matter) should be small and light-weight in order to help maximize range and/or allowable payload. At the same time, they must be structurally and thermally sound to withstand not only aerodynamic and thermal loads during high speed and during maneuver, but also any potential hammershock loads due to engine stall.

Inlets must also address Environmental issues. Sand, water, fog, salt/sea spray should not significantly impair their operation and performance. They must tolerate thermal cycles (freezing, thawing, heating and cooling) and must be serviceable and operable when icing conditions exist. In this case, either an ice detection system should be incorporated in order to alert the pilot to evade such conditions. Alternately, an anti-ice or de-ice system should be installed to either prevent ice buildup on inlet lips, for example, or remove ice that has accumulated. In addition, inlet systems on military aircraft should mitigate foreign-object-damage (FOD) in some manner such as a top-mounted integration or circuitous flow path to make it difficult for FOD to reach the engine face.

The third general requirements category for supersonic inlets is of course Aerodynamics and is the subject of this paper from here on. The inlets for supersonic military aircraft clearly must perform over different speed regimes. First and foremost, they must provide a sufficient quantity and quality of air to the engine over the operational flight envelope (Mach and altitude). The air they provide must have high total pressure coupled with low distortion (steady-state and dynamic) to ensure engine operability subsonically and supersonically. In addition, inlets should have low supersonic drag for efficient operation coupled with good low-speed performance.

C. Supersonic Inlet Design Selection

As mentioned, inlets for supersonic military aircraft are selected based on the design intent and mission of the aircraft. The maximum Mach number of the aircraft is the primary parameter governing inlet selection and design features. A general guideline is shown in Figure 2. There are two broad categories: (1) External Compression and (2) Internal Compression. For low supersonic Mach numbers, a normal-shock or so-called "pitot" inlet is sufficient. An example is the inlet on the F-86 "Sabrejet" or the F-16 Falcon as shown. Normal-shock inlets are generally acceptable for maximum Mach numbers less than 2 or so. Above that, some an initial wedge or ramp is needed in order to more gently and efficiently decelerate the flow. Again, depending on the maximum design Mach number, either one, two or three ramps are used [3]. A good example of a single-ramp supersonic inlet is the F/A-18 A/B and C/D as shown in Figure 2. Other examples are the F-22 and F-35 which feature so-called "wave-rider" inlet systems. For higher Mach numbers, more ramps are needed to efficiently decelerate the flow. Generally for Mach number significantly above 2, some sort of variable geometry is used in order to achieve decent performance over a wide Mach range. An example is the two-ramp F-4 Phantom and the three-ramp, articulating inlet system on the F-15 aircraft as shown in Figure 2. These designs are all "external compression" inlet systems where the flow is decelerated to subsonic conditions outside the inlet.

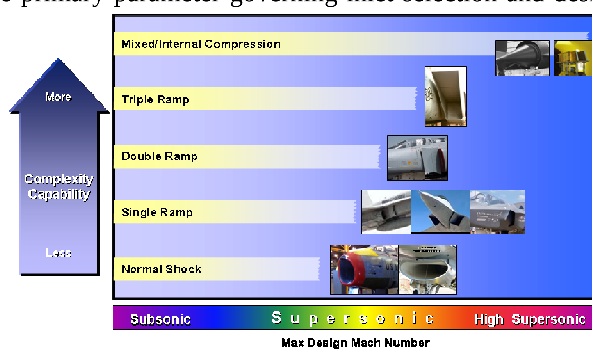
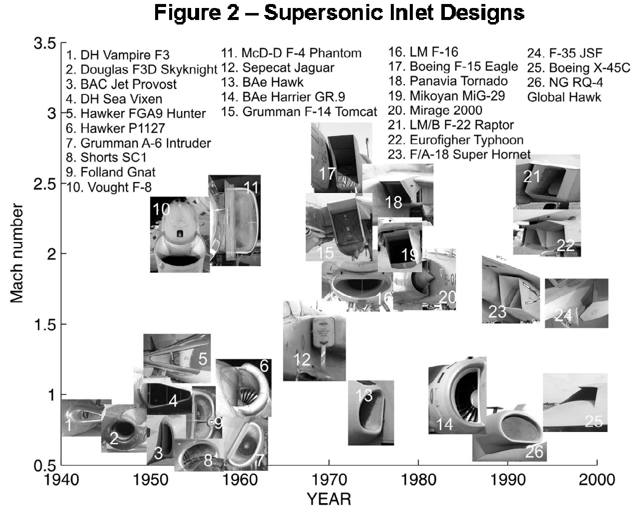


Figure 2 – Supersonic Inlet Designs



Reference: Figure 10 from: Sorbester, A., "Tradeoffs in Jet Inlet Design: A Historical Perspective", *Journal of Aircraft, Vol. 44, No. 3, May-June 2007. (Used with permission)*

Figure 3 – Fuselage-Mounted Intake Systems

For Mach numbers exceeding 3 or so, mixed or internal compression inlet systems are used. For mixed compression inlets, some of the compression occurs outside the inlet and some inside. For internal

[3] While the focus here is on two-dimensional inlets, the same guidelines generally apply to axi-symmetric inlets.

compression inlets, all compression generated by both oblique and normal shocks occurs inside the inlet. Examples of each are shown in Figure 2. The inlet on the SR-71 Blackbird is a mixed compression design with an axi-symmetric, translating spike to control both external and internal compression over a range of flight Mach numbers (Ref. 2). An excellent summary of different inlet designs and applicable Mach regimes is shown in Figure 3 which is taken from Reference 3.

D. Military Aircraft Supersonic Inlet Examples and Discussion Topics

This paper will highlight some of the common aerodynamic features of supersonic inlets for military aircraft. External compression inlet systems will be featured since that is the most common type on modern military aircraft. The F-15 inlet will be used as a representative example to illustrate some of these features and phenomena. In addition, the F-35 inlet will be examined as a more recent example of innovation and creativity in inlet design.

II. The F-15 Inlet System

The inlet system on the F-15 aircraft illustrates all the major aerodynamic features that need to be addressed by modern military aircraft inlet designers. An excellent summary of this inlet system and its development is presented in Reference 4. Each F-15 inlet is a two-dimensional external compression system mounted on side of the aircraft in the vicinity of the canopy. A close-up is shown in Figure 4. It is offset from the fuselage to allow the forebody boundary-layer flow to be diverted from entering the inlet. Each inlet has three movable ramps that allow the inlet capture area to be modulated based on flight condition to minimize effects on aircraft longitudinal stability and to optimize inlet drag. When operating supersonically there are three oblique shock waves and a terminal normal shock that coalesce near the lower inlet lip. These are illustrated in Figure 5. Also, highlighted in this figure are other main aerodynamic features of this inlet system. They are: boundary-layer diversion (already discussed above), oblique shock-wave boundary layer interaction (OSBLI), normal shock-wave boundary layer interaction (NSBLI), ramp and throat bleed/bypass, inlet spill, and inlet drag. Most, if not all of these are common aerodynamic features of supersonic inlets on modern military aircraft and will be discussed in more detail below.

Shock-Boundary Layer Interactions, or SBLI for short, have been the subject of intense interest and study over many years. An excellent summary replete with many references of extensive research is presented in Reference 5. Before the advent of computers and sophisticated numerical codes to solve the governing Navier-Stokes equations, many experiments were conducted to understand the flow physics at work. Schleiren or shadowgraph photography was used extensively to visualize both the shock wave as well as the affect the shock has on the boundary layer. The depiction in Figure 6 shows one such photograph as well as a sketch of the flow pattern and resulting additional compression and expansion waves generated by interaction with the boundary layer. The result is that the boundary layer is thickened in the vicinity of the shock and additional total pressures losses are incurred as a result. In addition, the boundary layer is less capable of withstanding any subsequent adverse affects such as an increasing pressure distribution. When this occurs, suction is often applied to remove low energy air.

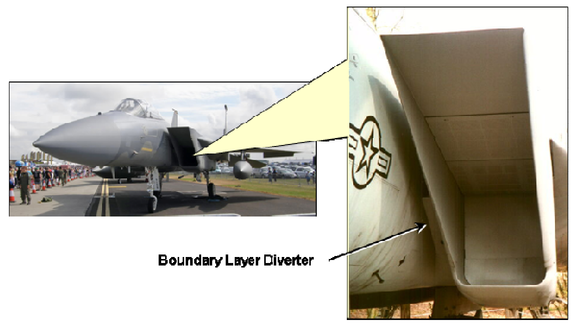


Figure 4 – F-15 Inlet System

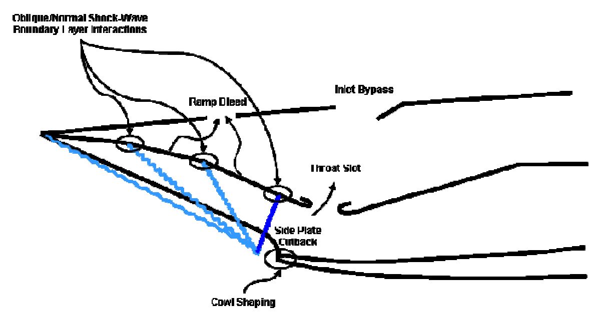
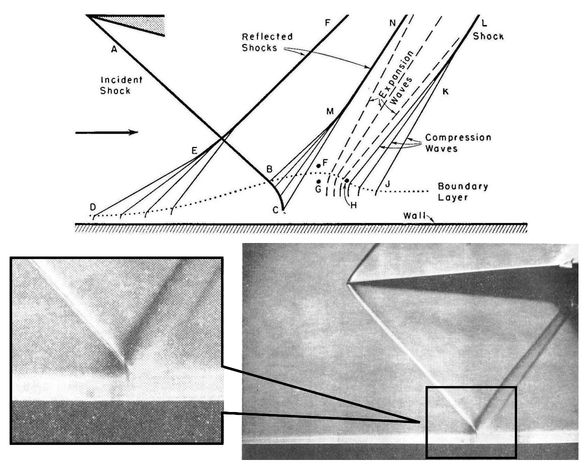


Figure 5 – F-15 Inlet System Aero Features



Reference: Shapiro, A. H., ***The Dynamics and Thermodynamics of Compressible Fluid Flow - Volume I***, The Ronald Press Company, New York, 1953, Figure 16.49, p. 582. (Used With Permission)

Figure 6 – Shock-Wave/Boundary-Layer Interaction

This is the case with the F-15 inlet. At the beginning of the second and third ramps, low-energy air is scooped off and dumped overboard (see Fig. 5). In addition, the entire surface of these ramps as well as the inlet sideplates contain an extensive array of bleed compartments and holes. This array removes more low-energy air to help maintain a stable shock structure, and thereby an acceptable level of inlet recovery and operability.

The F-15 inlet also features a large throat bleed slot that serves three functions. First, it removes the low-energy air left by the terminal NSBLI. Second, it offers a path for excess air captured by the inlet but not needed by the engine to be taken on-board the aircraft and then dumped over-board. This is called a throat bleed/bypass system and represents a philosophical approach to inlet design adopted over the latter part of the last century. The philosophy is that from an inlet system standpoint it is more efficient (i. e. lower drag and fuel consumption, higher thrust) to capture air that is not needed by the engine or other systems and then dump it overboard. Additional discussion on this topic follows. Thirdly, it was discovered during the F-15 inlet development program that using the throat slot as a bleed/bypass system mitigated the interaction effects of ramp and sideplate bleed on inlet performance and operability (Ref. 4).

Another main aerodynamic feature illustrated by the F-15 inlet system is spill. This occurs when the airflow provided by the inlet is more than what is demanded. The effect of inlet spill is to increase overall aircraft drag thereby decreasing net propulsive force and increasing fuel burn. This effect is much larger supersonically than subsonically. As mentioned, the philosophical approach has been to dump excess air overboard and incur the associated ram drag loss without the benefit of any thrust recovery. However, with the advent of variable-cycle engines (Ref. 6), there has been a shift in philosophy to bring excess air on-board and use it for avionics cooling, for example, and then recover some of the lost momentum elsewhere in the propulsion system. This has been found to be particularly beneficial at supersonic conditions when the effects of inlet spill are more pronounced. This is illustrated in Figure 7 which shows schematically the variation of inlet spill drag with inlet airflow. For subsonic operation, there is very little increase in inlet spill drag as inlet airflow (i. e. engine power setting) is reduced. However, supersonically drag due to inlet spill can be 5 to 10 times higher. To illustrate this point, consider a 2D external compression inlet designed and operating supersonically at M=2.0. Assume it has been sized such that the capture area, A_c, is 7.5 ft^2. The airflow captured by this inlet at 40,000 ft altitude is 273.3 lb/s.

$$\text{m-dot} = WTAP_0 * P_{t0} * A_c / \sqrt{T_{t0}}$$

$$\text{m-dot} = 0.3153 * 21.283 * 144 * 7.5 / \sqrt{702} = 273.3 \text{ lb/s}$$

Now assume that the aircraft can cruise at an engine power setting such that the required airflow is 85% of the capture airflow. This means that 15% of the airflow is potentially spilled around the inlet either around the cowl or sideplate lips. The momentum loss due to this spill flow amounts to a 2,647 lb increase in aircraft drag.

$$D)_{Spill} = 15\% * \text{m-dot} * M * a / g_c$$

$$D)_{Spill} = 0.15 * 273.3 * 2 * 968.1 / 32.174 = 2{,}647 \text{ lb}$$

An alternate approach would be to take this airflow on-board the aircraft, incur the associated ram drag, but recover some of the lost momentum by routing the excess airflow through the aircraft where up to 70 or 80% of the thrust may be able to be recovered. Consequently, the thrust loss (or drag increase) of over 2,600 lbs, can be reduced to less than 750 lb – a savings of some 1,800 lbs. In addition, the excess air could be used to help purge the engine bay of fuel fumes or supply air to an environmental control system. Adopting this philosophical approach has become more common place in modern supersonic inlet design for military aircraft.

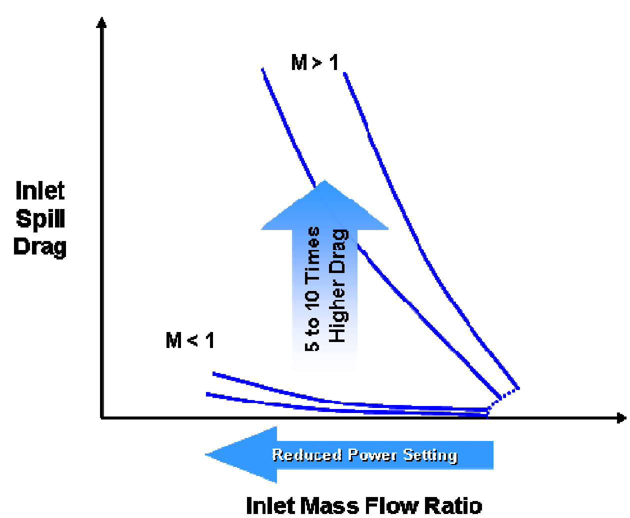


Figure 7 – Typical Inlet Drag Due To Spill

External cowl drag is another feature of the F-15 inlet system shared by today's military aircraft. Extensive experimental studies were conducted to arrive at the particular design on the F-15 cowl lip as well as the sideplate configuration. A balance was struck between what provided good subsonic recovery and low distortion whilst not significantly compromising supersonic performance. The importance of cowl shaping for good overall supersonic inlet system performance – recovery, distortion as well as drag – cannot be over-emphasized. In fact, a lower recovery supersonically can be offset by an inlet design with less drag resulting in a better overall installed thrust.

III. The F-35 Inlet System

The intake on the F-35 Lightning II aircraft is a so-called Diverterless Supersonic Inlet or DSI that utilizes a passive technique to manage flow both subsonically and supersonically. A picture of the inlet is shown in Figure 8, as well as a sketch from the patent for the inlet system concept (Ref. 7). This system has been under development since the early 1990's and was matured and "flight-proven" on an F-16 aircraft (Ref. 8). The main aerodynamic feature as described in the patent is an isentropic "bump" that passively diverts flow around the inlet to preclude ingestion of low-energy boundary-layer air without the use of a boundary-layer diverter such as is used of the F-15 inlet system. The bump surface also generates an isentropic conical shock system to decelerate flow through a series of isentropic compression waves prior to the terminal normal shock. The bump is defined from an inviscid flowfield generated by supersonic flow past an isentropic cone.

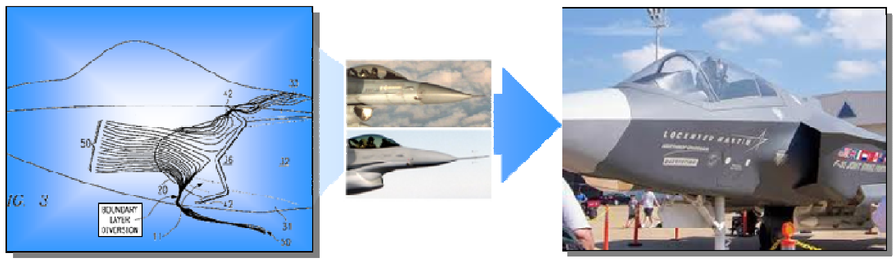


Figure 8 – F-35 Inlet System

While the concept is innovative and practical, the supersonic aerodynamic features are basically the same as with the F-15 inlet. There are OSBLIs as well as NSBLIs. These are highlighted in the left side of Figure 9. The OSBLI occurs at the base of the bump surface which generates the oblique shock. However, rather than managing this interaction with active bleed as is done on the F-15 system, the boundary-layer flow is controlled by the basic aerodynamic features inherent in the flowfield. Low-energy boundary-layer air is diverted around the inlet aperture as shown in the right side of Figure 9. This feature coupled with the use of isentropic compression on the bump eliminates the need for additional active flow control at the NSBLI location. The end result is a completely passive, fixed-geometry inlet system that has no moving parts, no bleed systems that could present environmental challenges (i. e. clogged bleed holes or slots), and is smaller and therefore lighter than comparable designs based on 2D flowfields.

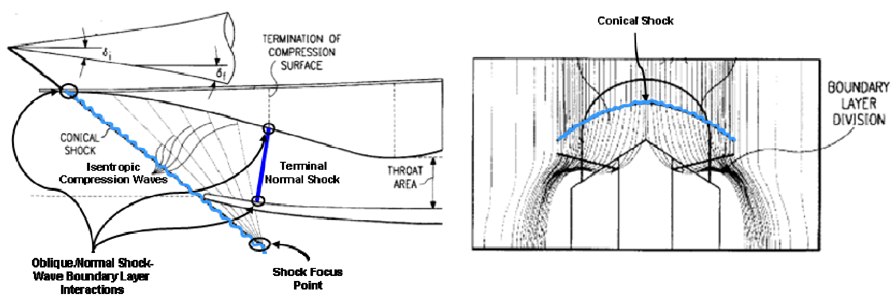


Figure 9 – F-35 Inlet System

Recall that inlets for supersonic military aircraft must also function well subsonically. Again the inherent aerodynamic feature of the F-35 DSI enables this to occur. Flow is also diverted subsonically in much the same manner as supersonically thereby providing high pressure air with low distortion to the engine. In addition, the benefits of capturing air rather than spilling it can also be realized on the DSI.

IV. Conclusion

The aerodynamics of supersonic inlets for military aircraft have not changed over the years. What has changed is our understanding as well as our ability to adapt and exploit those aerodynamic features. For example, the F-15 inlet system was developed with a series of half-a-dozen or so tests – both model-scale and full-scale. The F-35 inlet on the other hand was developed with extensive CFD analysis and only one high-speed model test [though there was considerable up-front investment and development (Ref. 8)]. Yet, the challenges faced by today's supersonic inlet designer are the same as those in the past. In order to provide high pressure air with low distortion, we must continue to understand and manage both OBSLIs as well as NSBLIs. In addition, we cannot overlook the affect inlet drag has on overall aircraft system performance. Continued and additional research should be focused in all these areas: OSBLI, NSBLI, flow control, cowl shaping, methods to mitigate the affect on inlet spill – particularly supersonically. A potential area for advanced research would be in morphing materials that could form blunt inlet/cowl lips for low-speed subsonic operation, yet become sharp for supersonic conditions.

References

1. Deskin, W. J., and Yankel, J. J., "Development of the F-22 Propulsion System", AIAA Paper 2002-3624.
2. SR-71 Flight Manual, Issue E: 31 October 1986, Change 2: 31 July 1989, URL: http://www.sr-71.org/blackbird/manual/.
3. Sobester, A., "Tradeoff in Jet Inlet Design: A Historical Perspective", *Journal of Aircraft*, Vol. 44, No. 3., May-June 2007.
4. Imeld, W. F., "The Development Program For The F-15 Inlet", AIAA Paper 74-1061.
5. Dolling, D. S., "Fifty Years of Shock-Wave/Boundary-Layer Interaction Research: What Next?", *AIAA Journal*, Vol. 39, No. 8, August, 2001.
6. "The ADVENT of a Better Jet Engine?", Defense Industry Daily, 1 October, 2007, URL: http://www.defenseindustrydaily.com/the-advent-of-a-better-jet-engine-03623/.
7. Hamstra, J. W., McCallum, B. N., Sylvester, T. G., Denner, B. W., and Moorehouse, J. A., "Transition Shoulder System and Method For Diverting Boundary Layer Air", US Patent 5,749,542; dated May 12, 1998.
8. Hehs, E., "JSF Diverterless Supersonic Inlet", 15 July 2000, URL: http://www.codeonemagazine.com/article.html?item_id=58.