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Flow control of a boundary layer ingesting serpentine diffuser via blowing and suction

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ABSTRACT

The use of serpentine boundary layer ingesting (BLI) diffusers offers a significant benefit to the performance of Blended Wing Body (BWB) aircraft. However, the inherent diffuser geometry combined with a thick ingested boundary layer creates strong secondary flows that lead to severe flow distortion at the engine face, increasing the possibility of engine surge. This study investigated the use of enabling active flow control methods to reduce engine-face distortion. An ejector-pump based system of fluidic actuators was used to directly manage the diffuser secondary flows. This system was modeled computationally using a boundary condition jet modeling method, and tested in an ejector-driven wind tunnel facility. This facility is capable of simulating the high-altitude, high subsonic Mach number conditions representative of BWB cruise conditions, specifically a cruise Mach number of 0.85 at an altitude of 12,000 m. The tunnel test section used for this experiment was designed, built, and tested as a validation tool for the computational methods.

1. Introduction

Serpentine diffusers allow for a centerline engine placement by ingesting the intake flow through an S-shaped duct. In this configuration, engines can be directly incorporated into an aircraft's airframe providing a number of benefits including increased accessibility for engine maintenance, drag reduction, and the reduction of thrust-related pitching moments. This type of diffuser was first incorporated into commercial aircraft in the early 1960s into designs such as the Hawker-Siddeley Trident, Boeing 727, and Lockheed L-1011.

In more recent years, serpentine ducts have been increasingly incorporated into newer aircraft designs due to their potential benefits. The explosion of interest in Uninhabited Air Vehicles (UAVs) has brought the use of serpentine diffusers to the forefront due to their inherent stealth capabilities and life-cycle cost implications. And, because these aircraft are typically used for high-risk reconnaissance operations, they need to be as stealthy and cost-effective as possible. Serpentine ducts have stealth implications because the engine face is a major source of radar signature [3].

A primary method of signature reduction in military aircraft is achieved by integrating the engine into the aircraft using a serpentine diffuser, which prevents direct radar line-of-sight to the engine face. Submergence of the engine inlet reduces the inlet ram drag as compared to a conventional pylon-mounted engine, and decreases the wetted area of the installation, thereby reducing the aircraft's parasitic drag. The elimination of the pylon also results in a decrease in weight due to the removal of the required supporting structure.

2. Boundary layer ingestion

To ensure maximum performance commercial aircraft engines are typically located in areas where the flow is relatively unobstructed, ensuring that the air captured by the diffuser is essentially uniform. Locations such as wing pylons provide the engine with a stream of relatively undisturbed flow. However, additional propulsive benefit can be derived from serpentine diffusers if the design also incorporates high levels of boundary layer ingestion (BLI), as indicated in Fig. 1.

By ingesting some of the boundary layer fluid, an effective increase in the aircraft's lift-to-drag ratio can be realized through the benefits of wake ingestion and wake filling [4]. The result is a decrease in operational fuel expenditure, and a decrease in overall aircraft life-cycle cost. At present, this type of installation is more typical of military aircraft configurations where it is often more critical to block direct line-of-sight to the engine face than worry about the aerodynamic consequences of adopting such a geometry.

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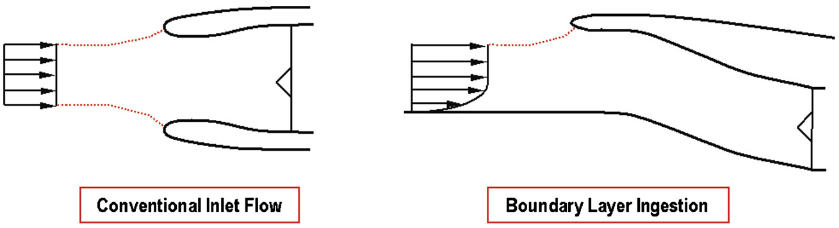

Fig. 1. Conventional vs. boundary layer ingesting inlets.

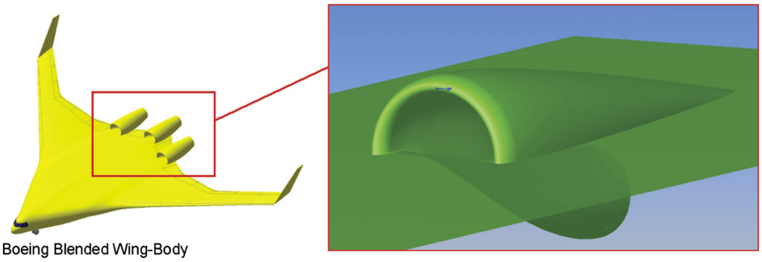

Fig. 2. BWB aircraft with a BLI serpentine inlet.

One of the major exceptions to the "typical" aircraft configurations is the Boeing Blended Wing Body (BWB) shown in Fig. 2.

The BWB is a flying-wing concept capable of significant performance benefits over the conventional tube-and-wing construction. Of particular interest is the incorporation of serpentine engine inlet diffusers coupled with significant amounts of boundary layer ingestion. If adopted, this configuration promises to have a large advantage over aircraft constructed using a more conventional design. In order to realize the large potential benefits, it will first be necessary to overcome the primary difficulty with serpentine BLI inlets, namely engine-face flow distortion.

3. Combined flow effects

Due to the physical curvature of serpentine inlets, the flow has a tendency to separate in areas of strong adverse pressure gradients, as well as induce strong secondary flows throughout the duct. Increased total pressure losses, as well as severe flow distortion at the engine-fan interface are characteristic of these types of systems. This trend is only increased in severity when coupled with designs that incorporate high levels of boundary layer ingestion. By introducing low momentum fluid to the inside turn of a serpentine duct, the severity of the cross-flow pressure gradients is increased. The high-momentum fluid from the outside turn collects the boundary layer fluid at the bottom of the duct creating a substantial circumferential total pressure distortion as depicted in Fig. 3.

The primary function of an engine intake duct is to deliver uniformly distributed airflow at a prescribed velocity to the AIP. A non-uniform airflow is considered to be distorted. Historically, experimentalists have found it is easiest to measure total pressure at the AIP, and thus, distortion descriptors are generally based on total pressure. AIP distortion can be categorized into two main types: radial and circumferential. In general, radial distortion (along blade span) can be neglected, allowing for the majority of focus to be based upon circumferential distortion. Circumferential distortion has a number of impacts on practical engine operation [5].

Most importantly, circumferential distortion has a direct impact on engine compressor operation, as depicted in Fig. 4 [6].

When the flow reaches the AIP and there is a substantial variation in total pressure across the face, more work is done by the

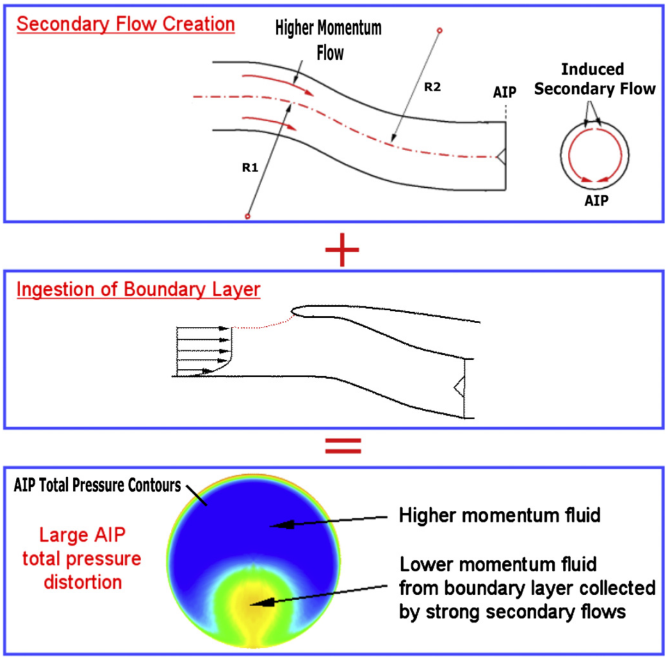

Fig. 3. Serpentine BLI inlets and distortion.

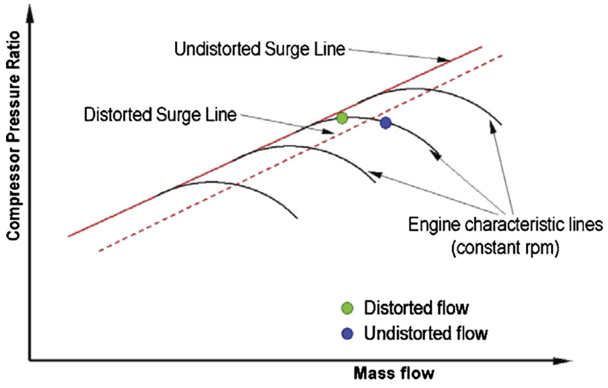

Fig. 4. Representative compressor map.