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Short communication

Effectiveness of vortex generator jets and wall suction on separated flows in serpentine-duct diffuser

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ABSTRACT

The present study describes the effectiveness of different flow control methods applied to a serpentine intake. Due to the geometry of the duct and diffusing nature of flow, the duct performs poorly as an intake, delivering low pressure and distorted air to the compressor. The problem can be alleviated by employing flow control on the duct. In this study, two types of flow control, namely steady vortex generator jets and boundary layer suction, have been applied and detailed measurements carried out. The performance of the duct has been evaluated with respect to static pressure recovery, total pressure loss and circumferential distortion at the exit. The amount of mass flow required to be added or removed for each method is also considered. It was found that the application of suction showed a greater improvement in total pressure recovery and reduction in circumferential distortion intensity compared to vortex generator jets. A combination of suction and vortex generator jets showed an improved performance compared to application of either. The improvements are attributed to reduction in flow separation region due to suction and a decrease in the effect of secondary flow due to vortex generator jets.

1. Introduction

Intakes are essential parts in air-breathing engines. For an aircraft gas turbine engine, in addition to acting as an air induction system, an intake is also expected to perform as a low-loss diffuser that delivers adequately uniform low-velocity, high-pressure air to the compressor. Intakes have been known to contribute substantially to the overall radar cross section of the aircraft, which is disadvantageous for military aircraft. By introducing appropriate bends in the intake, it is possible to break the direct line of sight to the compressor or fan blades, thus reducing the radar visibility of the aircraft [27]. Further, due to the high thrust-to-weight ratio requirement, it is essential that the length of the intake be a minimum. As a result, the design of an aircraft intake system for typical military applications calls for one with a high centerline offset and a short length.

When a fluid flow encounters a bend in its path, the curve introduces secondary flows due to gradients in the boundary layer [8,2]. In addition, the short length in a diffusing flow intensifies the adverse pressure gradient, promoting flow separation. The combined effect of formation of secondary flows and boundary layer separation results in a penalty on the performance of the intake in terms of total pressure losses and distortion at the compressor inlet. With increasing area ratio, flow through the curved diffuser follows three regimes: a regime of well-behaved and apparently attached flow, a regime of transitory stall where the separation varies in size and intensity with time and, finally, a regime of fully developed stall [5].

In order to overcome the aerodynamic losses caused by the geometrical limitations, there is enormous incentive to investigate the effectiveness of various types of flow control schemes and understand the flow phenomena associated with them. The flow control methods [7,6] are broadly classified into velocity profile modifiers, momentum addition to near-wall flow, moving-wall configurations and turbulators. Flow control may also be classified as *active*, where an auxiliary device is used to exchange energy with the main flow, or *passive*, where there is only a local redirection of flow. Active flow control has the advantage of being able to adapt to the flow conditions in real time. An example of passive flow control is the use of vortex generators (VGs), which are fin-like protrusions from the wall within the boundary layer that enhance mixing by the transfer of momentum from the outer fluid to the boundary layer fluid by forming vortices. Passive low-profile vortex generators have shown the best improvement in distortion and total pressure recovery in S-ducts when applied just upstream of separation location [17]. Tapered fin vortex generators

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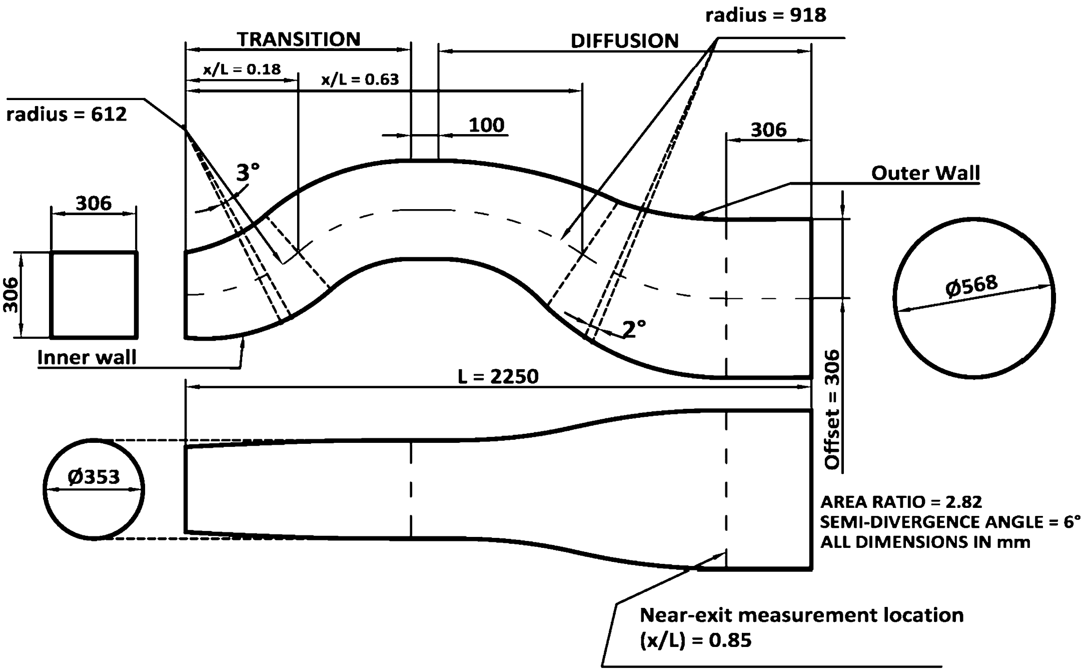

Fig. 1. Serpentine duct dimensions.

and boundary layer fences [23] are also effective in controlling secondary flows in two-dimensional S-ducts. As with all passive flow control devices, although they do not require an auxiliary power to function, vortex generators suffer a drag penalty, chiefly during periods when their function is not required. In contrast, vortex generator jets (VGJs) are active devices that create vortices by injecting a jet into the main flow. They were first used by Wallis [26,9] who also developed it to be useful in delaying turbulent separation. The performance was evaluated based on skin-friction coefficient and static pressure measurements. The jets interacting with the freestream flow produced longitudinal streamwise vortices that were found to reduce the separation extent by bringing about cross-stream mixing. By injecting a mass flow of about 0.1% of the main flow, VGJs have shown improvements in terms of total pressure recovery and distortion [14]. Control of separation over the lip of an intake subjected to cross wind by using boundary layer trips and VGJs is shown to be possible due to increased turbulence intensity [25].

Separation can also be delayed by modifying the velocity profile by means of adding or removing mass near the wall [10]. The effectiveness of suction in delaying separation on a circular cylinder was first shown qualitatively by Prandtl [15]. By applying suction through finely perforated sheet, with suction velocity ratios of the order of 0.004, the turbulent boundary layer thickness was significantly reduced, and at around 0.01 the turbulent boundary layer approached a constant-thickness laminar boundary layer [4]. Sano and Hirayama [18] have found suction to be effective in preventing flow separation as the skin-friction coefficient was found to be higher when suction was applied. Tests on highly offset diffusers with suction and blowing were performed by Ball [1] and the study showed that a good performance can be obtained from highly offset diffusers by employing small amounts of wall suction and blowing upstream of the separation point.

Previous studies performed on the serpentine duct employed in the present experiments have included steady [24,21] and pulsed VGJs [3]. By employing a mass flow rate of 0.13% in steady vortex generator jets, an improvement of 9% was found in total pressure losses. In the present study, VGJs and boundary layer suction were applied to the duct, separately and then together, and the relative improvement in performance was evaluated with respect to the duct without flow control. Since boundary layer suction is known to suppress flow separation and VGJs to control secondary flows, the present study includes a test condition where the effect of applying both is studied.

2. Experimental setup

The studies were performed using an open-circuit wind tunnel with exit dimensions 305 mm × 305 mm delivering air at an average velocity of 28 m/s. The turbulence intensity in the freestream direction has been measured to be less than 0.5%. Reynolds number based on test section width was 6.5×10^5 and the Mach number 0.1 for the present study. The wall boundary layer thickness at the tunnel exit is equal to 0.2% of the test-section width [14].

Fig. 1 shows the drawing for the serpentine duct used in this study. It consists of two parts: a square to circular transition section and a circular to circular section. The duct was instrumented with pressure taps along the inner and outer wall centerlines, as defined in Fig. 2. In addition to the streamwise measurement taps along the inner and outer wall centerlines, a set of taps were placed towards the end of the diffusing $x/L = 0.85$ in the circumferential direction. In addition to static pressure taps, Preston tubes were also employed to indirectly detect flow separation. Preston tubes are essentially an L-shaped total pressure tube near the wall which provides the local skin friction value with suitable calibration [16]. For the present purposes, the differential pressure reading from each Preston tube and the adjacent static port is used to determine the location of flow separation. When flow separates from the wall creating a recirculation zone, the time-averaged pressure sensed by the static and Preston tubes are approximately the same. In other words, when there is flow separation, c_f^* is zero or sometimes slightly less than zero, thus providing a qualitative way of determining flow separation [22]. The design of the Preston tubes employed here was based on that of Patel [13]. Static and Preston tubes were also located along the circumference of the duct, at a distance of 306 mm from the exit of the duct (at $x/L = 0.87$), as shown by the plane marking the "near-exit