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SWIRL DISTORTION USING STREAM VANES FOR BOUNDARY LAYER INGESTION RESEARCH

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ABSTRACT

The swirl distortion of a StreamVane™ was investigated in the NASA Glenn Research Center W8 test facility. The StreamVane™ was designed and generated by Virginia Tech based on CFD simulations and included a center body at the aerodynamic interface plane. The swirl pattern generated by the distortion was evaluated using a dense grid of 5-hole Pitot probe measurements captured using a rotating array of probes. Good agreement was found between the design intent and the results at 38.5 kg/s mass flow. The StreamVane™ swirl results were compared to clean facility flow at 5 inlet mass flows and found to be consistent. Additionally, the axial location of the StreamVane™ relative to the measurement plane was investigated to determine the impact on downstream total pressure loss generated by the vanes. The intent of this work was to assess the viability of using a StreamVane™ to generate a Type I or Type II distortion into a Boundary Layer Ingesting propulsor to assess its aerodynamic performance and aeromechanic response.

INTRODUCTION

For decades it has been proposed that wake ingestion could be beneficial to aircraft propulsion similar to its benefit to marine propulsion. Application of such techniques has been limited in air breathing propulsion for a number of reasons, including feasibility of ingesting large enough volumes of the boundary layer for the benefit to be seen, and building highly efficient engines that can withstand the loads generated by the highly distorted flow. In 1993 Smith outlined the math to quantify the potential benefit of such a coupled airframe-propulsor system [1].

The distortion caused by the boundary layer results in two distinct but highly coupled phenomena which impact engine performance. First, the total pressure loss as a result of distortion results in decreasing the total pressure in front of the fan and therefore increasing the pressure ratio across it [2]. Total pressure distortion has been extensively studied, and the use of pressure screens has been used to simulate the effect in labs for decades [3, 4]. Second, the swirl changes the incidence angle of the flow at the inlet. If this angle variation is large enough, the flow over the fan blades can separate, reducing the efficiency of the system.

Measurement of swirl has been a concern for several years and there are guidelines for the measurement of swirl for engine development [5]. The SAE Methodology for Assessing Swirl Distortion [5] includes numerous examples of engines ingesting swirl and the consequences to performance, particularly to military aircraft applications. Several methods to simulate swirl are also discussed in the SAE document [5]. These include turning vanes, use of wing tip vortices, and use of swirl chambers. The examples given are for typical swirl patterns (bulk swirl, twin swirl). Simulation of patterns of more complicated flows has been difficult to create reliably due to the complex structures needed and the cost of manufacturing such devices [6].

With recent advances in aircraft designs that include hybrid-wing bodies and electrically driven or enhanced aircraft, the potential benefits of Boundary Layer Ingesting aircraft are growing. System studies have shown a number of potential aircraft that would benefit from Boundary Layer Ingestion (BLI) technology.

One study by Kawai et al. found that a compact aft-mounted BLI propulsion system could provide 3 - 5 % fuel burn reduction relative to standard pylon-mounted configurations [7]. In 2012 Hardin et al. did system studies on more advanced configurations and found up to 10% benefit [8]. Turnbull compiled a list of analyses showing between 3 and 10% benefit [9].

Building on these studies, an integrated Fan and Inlet test was performed at NASA Glenn Research Center's 8-foot-by-6-foot wind tunnel. The Boundary Layer Ingesting Inlet/Distortion Tolerant Fan (BLI^2DTF) test obtained detailed fan performance measurements of a distortion tolerant fan designed in conjunction with a boundary layer ingesting inlet [10] and a Variable area nozzle. Results at Mach 0.78 in NASA GRC's 8-foot-by-6-ft wind tunnel agreed well with CFD, proved the fan's robustness, and showed better than anticipated performance at design conditions [11].

STREAMVANE DESIGN USING CFD

While the NASA BLI^2DTF fan test was incredibly informative regarding both the benefits of BLI for fans and the ability of fans to withstand the loads associated with this environment, it also exemplified the complexity of the problem faced when integrating propulsors with airframe bodies. The propulsor interacts with the incoming flow, changing it, and this interaction is not fully understood. The flow itself is highly complicated, and the structures impacting the fan are difficult to measure due to access constraints. Parsing the impact of swirl, total pressure distortion, and static pressure distortion is very difficult.

Recently Virginia Tech University developed patented technology to produce distinct swirl patterns based on CFD. The product, a StreamVane™, creates the swirl by placing curves everywhere perpendicular to the desired flow. The complex structures are created using additive manufacturing. Their ability to produce the desired flow and be structurally robust has been investigated [6, 12–14].

The purpose of this study was to validate the flow field generated by the StreamVane™ in NASA Glenn Research Center's W8 facility. Once the method of StreamVane™ design and implementation in this facility is established, studies of fans behind StreamVanes™ can be utilized to gain initial understandings of the impact of various swirl structures on fan performance. Utilizing StreamVane™ technology allows the study of several components of BLI independently [15]. StreamVanes™ can be produced relatively quickly and relatively inexpensively based on CFD models of the flow. Placing the StreamVane™ in the inlet upstream of a fan will then allow us to study the impact of swirl on fan performance. Total pressure distortion screens can then be added to the design of future iterations to obtain representative total pressure distortion with swirl.

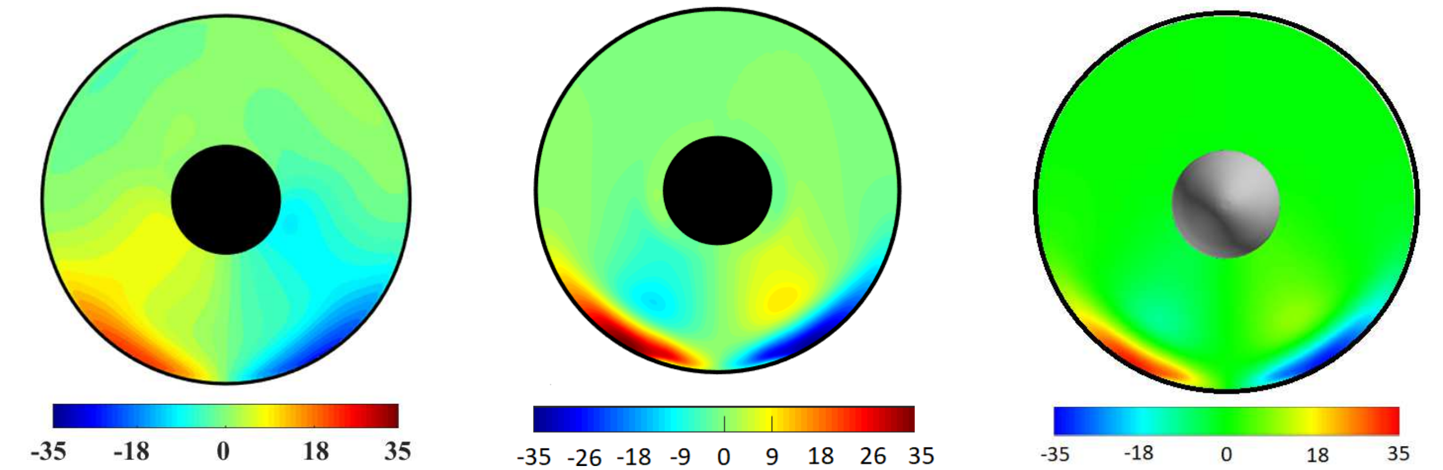
To design a StreamVane™ geometry, first a target distortion profile at some desired distance downstream of the StreamVane™ is defined. For this study United Technologies Computational Fluid Dynamics (UTCFD) simulation of the NASA BLI^2DTF Fan flow field at the Aerodynamic Interface Plane (AIP) was chosen. This simulated flow field is shown in Fig.1a. Prior to this work, StreamVane™ swirl distortion generators had been constructed to produce the desired swirl in an open, cylindrical duct based on a target profile that occupied the entire duct cross-sectional area. In this case, however, the target profile contains a spinner which produces radially outward flow along the spinner and an annular distortion profile. The target profile (at the AIP) was used to produce a corresponding profile at the StreamVane™ trailing edge, using StreamFlow, a computational method developed at Virginia Tech. A conceptually similar technique, operating on a pressure-velocity formulation and utilizing the open-source CFD code OpenFOAM, can be found at [16]. While the method described was effective at solving the forward problem (producing a downstream AIP profile based on a known StreamVane™ exit profile), it was not suitable for directly solving the inverse problem (finding the necessary StreamVane™ exit profile to produce a desired AIP profile) due to numerical instability. A rewritten and unpublished version of StreamFlow, based on the vorticity transport equation and implemented without a dependency on OpenFOAM, has been developed at Virginia Tech to accurately solve both the forward and inverse propagation problems. This method was used to perform the propagation for this case. The output of this method was then validated by using ANSYS CFX to propagate the StreamVane™ exit profile downstream, and compare the resulting profile at the AIP to the AIP target profile.

The expected swirl angles at the AIP when the StreamVane™ is placed 0.53 diameters upstream, with an inlet mass flow of 41 kg/s (90 lbms/s, test section inlet Mach number of 0.44) based on the Virginia Tech CFD is shown in Fig.1b. When comparing this to the target profile shown in Fig.1a, it is apparent that the large scale swirl structures are well matched. However, in the region between the strongest swirl structures and the centerbody the StreamVane™ produces low magnitude swirl structures rotating counterclockwise to the boundary layer swirl structures produced by the Boundary Layer Ingesting interface.

The StreamVane™ performance at the AIP was also modeled by NASA GRC using the TURBO code, and the results of the swirl angle are shown in Fig.1c. The two simulations match very well. A rendering of the final design produced by this process is shown in Fig.2.

TEST DESCRIPTION

In order to validate the ability of the StreamVane to create a swirl profile representative of the BLI^2DTF geometry, a test was performed in the Single Stage Axial Compressor and Fan facility in W8 of NASA Glenn Research Center's Engine Research Building. Air flows through a filter housing into a 122 cm



(a) UTCFD PREDICTION OF DESIRED SWIRL ANGLE.

(b) VIRGINIA TECH CFD PREDICTION OF STREAMVANE PROVIDED SWIRL ANGLE.

(c) GRC CFD PREDICTION USING TURBO OF STREAMVANE PROVIDED SWIRL ANGLE.

FIGURE 1: CFD PREDICTIONS OF THE THE SWIRL AT THE AIP AT 41 KG/S MASSFLOW.

FIGURE 2: RENDERING OF THE FINAL STREAMVANE DESIGN.

(48 inch) pipe, mass flow is measured using a 88.9 cm (35 inch) orifice plate, the flow is turned through two 90-degree bends, then goes through several screens and honeycomb in to a settling plenum before being re-accelerated in to a 56 cm (22 inch) diameter pipe. The 56 cm diameter test section has a 17.75 cm (7 inch) diameter nose cone at the end of the shaft where rotating machinery is normally mounted. This nose cone was left in to provide representative flow for when the propulsor is installed during later investigations.

Five mass flows that span the available mass flow range of the facility were investigated: 13.6, 22.7, 31.8, 38.5, and 45.4 kg/s (corresponding to test section inlet Mach numbers of 0.014, 0.23, 0.32, 0.41, and 0.48). Because independent CFD studies were done at 41 kg/s (90 lbm/s, Mach number of 0.44), the results presented focus on the 38.5 kg/s results to be as close as possible to compare. Table 1 shows the different mass flow and inlet Mach number values considered for different cases.

Five rakes of 5-hole pressure probes were manufactured and installed in the AIP rotating rake array used during the BLI^2DTF test. Each probe was calibrated in NASA GRC's CE-12 calibration facility through +/- 25 degrees in both pitch and yaw at Mach 0.2, 0.3, 0.4, 0.5 and 0.6. The array is capable of 270 degrees of rotation. Because the majority of the distortion produced by this fan-airframe configuration is on the outer radius between

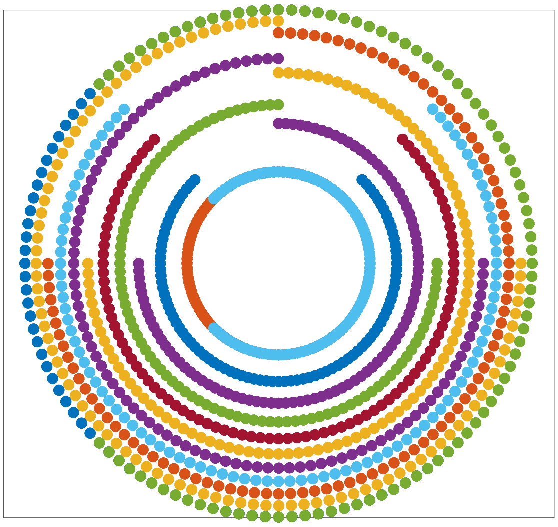


FIGURE 3: SCHEMATIC OF 5-HOLE PROBE MEASUREMENT LOCATIONS.

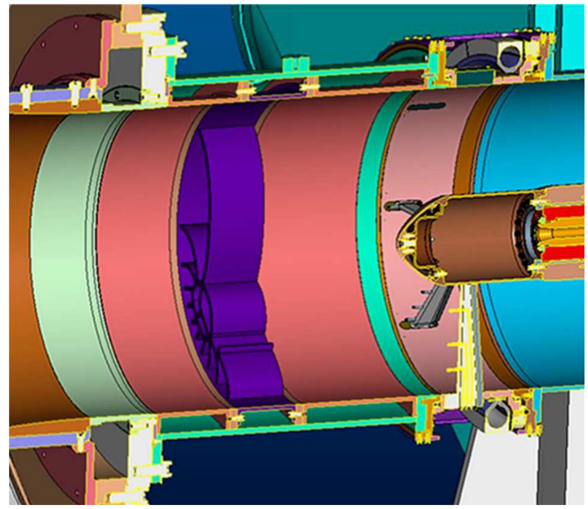


FIGURE 4: DEPICTION OF STREAMVANE IN TEST SECTION AT DESIGNED LOCATION WITH RAKES INSTALLED AT AIP.

TABLE 1: MASS FLOWS AND MACH NUMBERS OF CONSIDERED CASES.

case	Mass Flow (kg/s)	Inlet Mach Number
UTCFD	41	0.44
VT CFD	41	0.44
NASA TURBO	41	0.44
Test 1	13.6	0.01
Test 2	22.7	0.23
Test 3	31.8	0.32
Test 4	38.5	0.41
Test 5	45.4	0.48

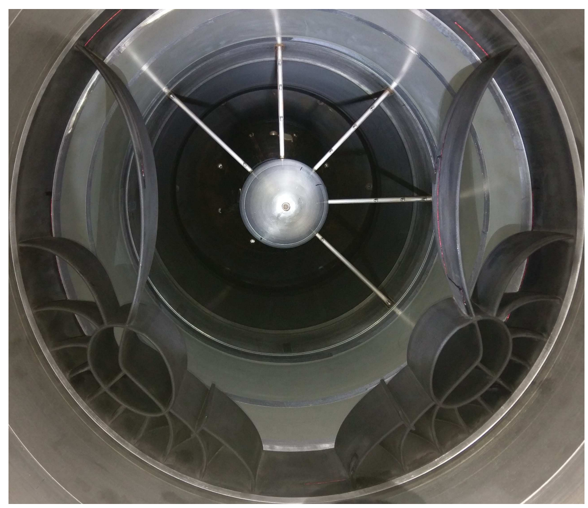


FIGURE 5: PICTURE OF THE STREAMVANE INSTALLED AT THE DESIGN LOCATION WITH THE 5-HOLE PROBE RAKES INSTALLED AT THE AIP.

130 and 270 degrees (forward looking aft clockwise with zero being top-dead-center), two rakes were created with probes at the outer-most radii. The other three rakes had probes at differing radii. When the array was rotated every three degrees, the dense measurement grid shown in Fig.3 is obtained. The colors represent the locations measured by a single probe.

The rotating rake of 5-hole probes was placed at the Aerodynamic Interface Plane (AIP). The StreamVane™ was designed to go 29.8 cm (11.75 inches) upstream of the AIP. The duct was designed in a modular fashion such that the location of the StreamVane™ relative to the AIP could be varied by manually moving it. A schematic of the set up is shown in Fig.4. For this investigation the design location was investigated, as well as the configuration placing the StreamVane™ 44 cm (17.4 inches) upstream of the AIP to determine the impact of distance on the flow structures produced. A picture of the StreamVane™ with the 5-hole probe rakes installed downstream is shown in Fig.5. The second location placed the StreamVane in the region that is pink upstream of the design location shown in the figure.

RESULTS

The swirl angle measured at the AIP for a clean inlet (no StreamVane™ installed) and a mass flow of 38.5 kg/s (85 lbm/s, Mach = 0.41) is shown in Fig.6a. The clean flow is very uniform with negligible swirl.

The measured swirl with the StreamVane™ placed at the design location is shown in Fig.6b. The coherent structures that the StreamVane™ was designed and predicted to produce are clearly evident and match the CFD shown in Figs.1b and 1c well in both size and magnitude.

To determine the impact of the distance between the StreamVane™ and the measurement plane, the StreamVane™ was moved to the upstream location. The measured swirl angles are shown in Fig.6c. Qualitatively there appears to be very little impact on the swirl when the StreamVane™ is further from the measurement plane.

Averaging the swirl across the radius (from the spinner to the test section wall) at each circumferential location (0 being top dead center and moving clockwise around the test section) provides an understanding of the swirl structures around the test section. These values are shown for all the investigated mass flows in Fig.7a for the design location and Fig.7b for the upstream location of the StreamVane™. As expected, the averaged swirl angle is very close to zero except in the lower quadrant where the two counter-rotating structures are seen in Figs 6b and 6c appear as a high positive average swirl around 130 degrees and very negative swirl around 170 degrees. Very little change is noticed as the mass flow increases. The results at 38.5 kg/s (inlet test section Mach = 0.41) are shown for both the design and upstream placement conditions in Fig.7c. Looking at the averaged results it is evident that the averaged swirl magnitude is slightly reduced in both of the swirl structures when the StreamVane™ is moved upstream.

The swirl intensity, or extent weighted absolute swirl, for each radius i as defined by the SAE [5] is

$$SI_i = \frac{SS_i^+ \times \theta_i^+ + |SS_i^-| \times \theta_i^-}{360},$$

where SS is the average positive (+) or negative (-) swirl content at the radius (i) and θ is the extent of the positive (+) or negative (-) region of swirl in degrees. Basically is is an average measure of the absolute value of the swirl at each radius. The Swirl Intensity for the StreamVane™ at the design location and all of the mass flows tested. The swirl intensity is negligible except for the outer 20% of the radius, which makes sense considering the location of the greatest swirl structures. The swirl intensity does not change when the StreamVane™ is placed at the upstream location, as shown in Fig.8b.

The vanes for this StreamVane™ were not streamlined and had fairly blunt trailing edges. As a result, a total pressure distortion was seen downstream. The total pressure ratio between the incoming flow and the AIP is shown in Figs.9a - 9c for the clean in-flow, StreamVane™ at the design location, and StreamVane™ at the upstream location. Moving the StreamVane™ did not significantly alter the losses due to the vanes. Future iterations will need a tapered trailing edge to mitigate this effect.

Conclusion

A StreamVane™ was designed and created to simulate the swirl measured by the NASA Boundary Layer Ingesting Inlet/ Distortion Tolerant Fan test. The swirl produced by the StreamVane™ was measured in the Single Stage Axial Compressor and Fan Facility at NASA Glenn Research Center using a dense grid of five 5-hole probe rakes rotated around the flow field. While the StreamVane™ could not produce the exact profile desired, the structures were close enough to determine the potential impact on fans in future tests. The resulting flow field was found to match CFD predictions of the StreamVane™ performance very well. The total pressure downstream of the StreamVane™ clearly showed the vane structure. Future iterations will be optimized to minimize total pressure distortion due to the vanes. Additionally, future iterations of this device coupled with total pressure loss screens could provide the appropriate upstream boundary conditions for further boundary-layer ingestion investigations. Future tests placing the StreamVane™ in front of a rotating fan with and without total pressure screens will aid in understanding the impacts of swirl and total pressure due to boundary layer ingestion on fans.

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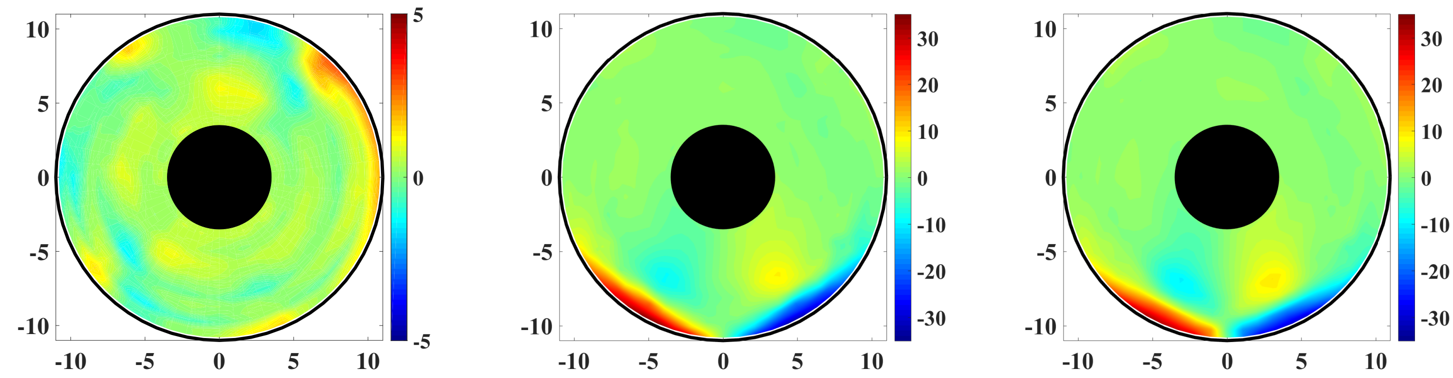
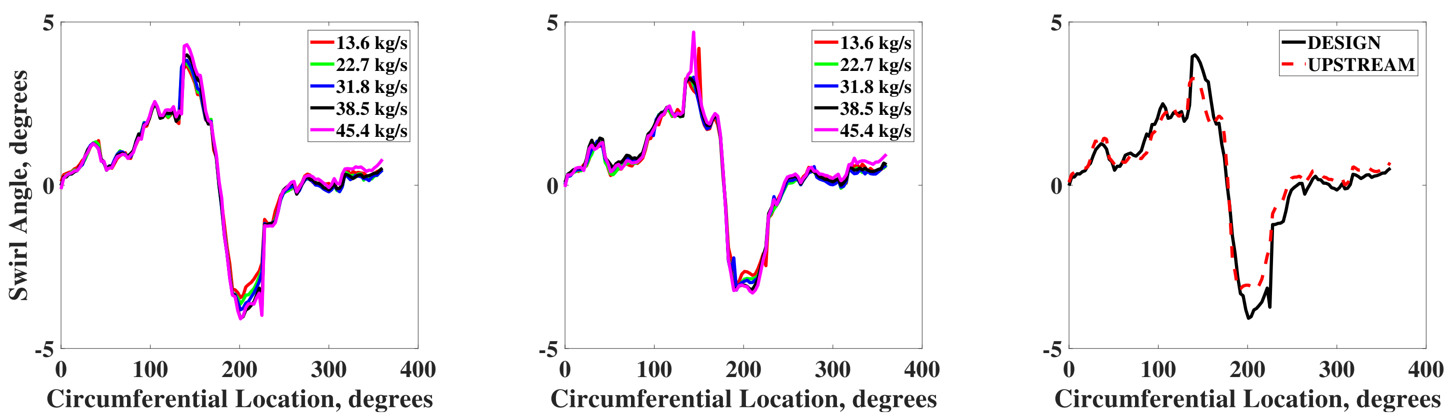


(a) EMPTY TEST SECTION

(b) STREAMVANE AT DESIGN LOCATION

(c) STREAMVANE AT UPSTREAM LOCATION

FIGURE 6: SWIRL MEASUREMENT (DEGREES) AT THE AIP AT 38.5 KG/S (MACH = 0.41).

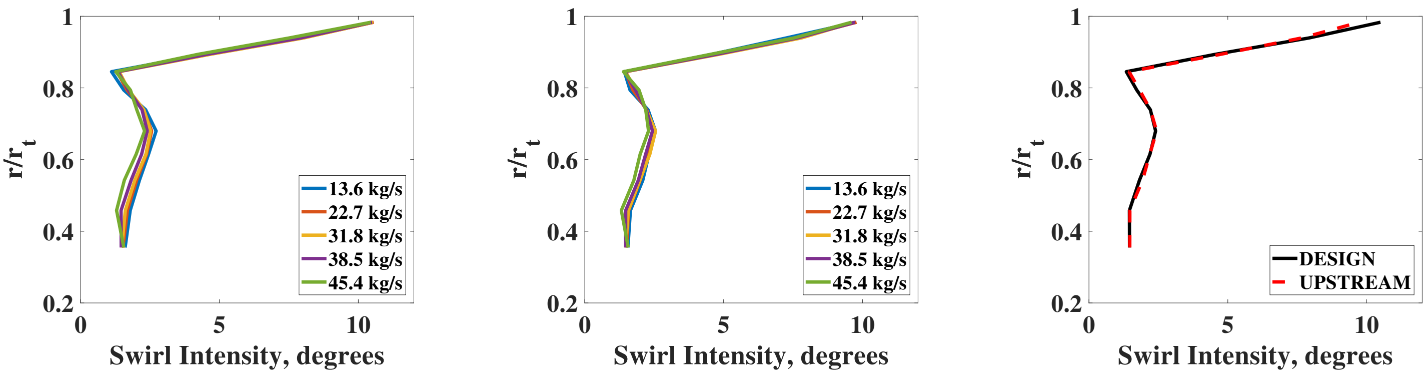


(a) DESIGN LOCATION

(b) UPSTREAM LOCATION

(c) DESIGN LOCATION COMPARED WITH UPSTREAM LOCATION.

FIGURE 7: RADIAL AVERAGE OF SWIRL ANGLE AT EACH CIRCUMFERENTIAL MEASUREMENT LOCATION, 38.5 KG/S (MACH = 0.41).

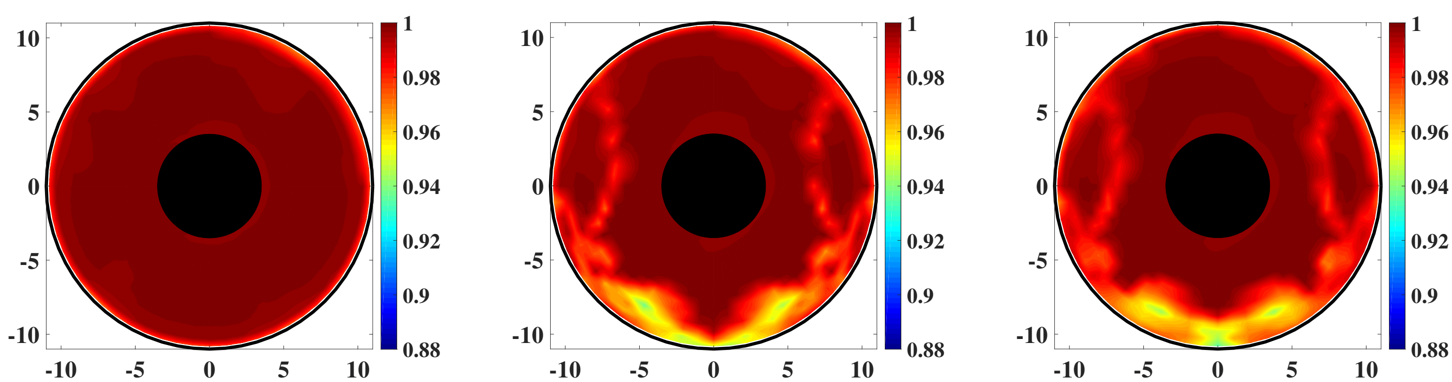


(a) DESIGN LOCATION

(b) UPSTREAM LOCATION

(c) DESIGN LOCATION COMPARED WITH UPSTREAM LOCATION

FIGURE 8: MEASURED SWIRL INTENSITY AT 38.5 KG/S (MACH = 0.41).



(a) EMPTY TEST SECTION

(b) DESIGN LOCATION

(c) UPSTREAM LOCATION

FIGURE 9: MEASURED TOTAL PRESSURE RATIO AT 38.5 KG/S MASSFLOW (MACH = 0.41) in PSID.

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