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AUTOMATION SCHEME IMPLEMENTING PASSIVE FLOW CONTROL IN NUMERICAL S-DUCT ANALYSIS

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ABSTRACT

Aircraft design is dependent on its major components, including the propulsion system. In an aircraft with embedded engines, S-duct diffusers are used to direct and diffuse inlet air to the conditions required by the compressor. When high-speed flow travels around the internal bends the flow can separate and total pressure can distort. In previous experimental work, passive flow control in the form of tubercles has been implemented manually to help reduce or eliminate separation regions in the S-duct. Design of S-duct is done through experimental testing and numerical modeling. In previous work CFD has followed the experimental work. In this work an automation scheme was created to allow numerical design to be performed before costly experimental analysis. An automation scheme was created to implement tubercles into the S-duct inner radii, defined by three key parameters: positive amplitude, negative amplitude and wavelength. These parameters are fed into a script which develops the tubercle profile, overlaid onto the baseline S-duct geometry for the set location. The profile ensures the flow area is maintained constant for each design so as not to add any constriction.

INTRODUCTION

S-ducts on aircraft are used when gearbox or propellers require offset inlets or where the engine is embedded in the fuselage. In transonic flight, the S-duct must diffuse the incoming air to the conditions required by the compressor. The compressor is highly dependent on inlet conditions and the uniformity of the flow. Non-uniformity can create instabilities in an engine which can lead to mechanical stress or surge. Through modifying the S-duct more uniform pressure and velocity can be delivered to the compressor.

S-ducts with various offset, length and aspect ratio have been investigated at the Royal Military College of Canada (RMC) [1–3]. Separation and distortion occur throughout the S-duct leading to poor exit conditions with non-uniform total pressure and velocity. To overcome this, passive flow can be added in the form of a bio-inspired geometry, known as tubercles. Tubercles are designed based on the undulations from the pectoral flipper of a humpback whale, depicted in the bottom of Figure 1. Experimentally, a uniform sinusoidal tubercle pattern is typically chosen for the leading edge design.



FIGURE 1: Humpback whale pectoral flipper tubercles [4]

In 2001, Fish *et al.* implemented tubercles on the leading edge of a NACA 63₄ – 021 airfoil [5]. They proved that this can reduce the severity in lift decrease post-stall and help to keep flow attached at higher angles of attack. Tubercles have been applied to other lifting surfaces such as low pressure turbine (LPT) blades, Pym *et al.* [6]. In implementing tubercles on LPT blades it was found that even at low Reynolds numbers the tubercles were able to generate stream-wise vortices along the airfoil. Tubercles have also been implemented on wind turbines by Ibrahim *et al.* where it was determined that tubercles did not improve the power coefficient however, in unsteady conditions, they outperformed the baseline blade [7]. On an internal aerodynamic surface, the tubercles are needed along the inner radii of both bends, discussed below.

Vakili and Wu began looking into compressible flow in S-ducts and performed a comparison between computational and experimental work [8]. The Navier-Stokes based numerical procedure was able to predict accurately similar flow field but under-predicted distortion at the duct exit, also known as the Aerodynamic Interface Plane (AIP). Noting this distortion, research focused on the implementation of passive and active flow control. Anderson tried passive flow control on the inner radii in the form of vortex generator vanes to prevent separation [9]. They were able to significantly lower engine face distortion with a small reduction in total pressure at the AIP.

Anabtawi *et al.* looked into S-duct flow at a high subsonic Mach number of 0.85 [10]. They implemented vortex generators and found large vortex generators that protruded outside the boundary layer were effective in increasing the total pressure recovery and reducing distortion. Tournier *et*

al. tested at Mach 0.95 and found that imputing vortex generators was effective in reducing distortion and improving pressure recovery [11].

Research on high subsonic S-ducts has been continued at RMC investigating the effects of offset, length and aspect ratio on the baseline geometry [1]. Further investigation was done on the baseline S-duct to implement passive flow control in the form of tubercles to see the benefits on the exit conditions [12]. Various tubercle geometries have been tested and they have proved effective in increasing the total pressure recovery. The findings have been validated through numerical studies by Hickling [13], Schneider [14] and Rider *et al.* [15].

COMPUTATIONAL SETUP

Previous numerical work at RMC led to the decision to use the $k - \epsilon$ Shear Stress Transport (SST) turbulence model [16]. The parameters for this model were left unchanged and the focus was directed towards automation of the mesh generation process for new tubercle geometries. The process of numerically modeling S-ducts prior to experimental testing has not been investigated at RMC and can expedite the S-duct design process. In previous work, the separation point of flow along the S-duct inner radii was determined for the baseline (no tubercle) S-duct. These two points were then used for implementing passive flow control coincident with the emergence of tubercles from the duct walls, leading to counter rotating vortices forming prior to the regions of separation. Figure 2 shows the S-duct locations where flow control was applied as well as the experimental static pressure ports along the top and bottom meridians.

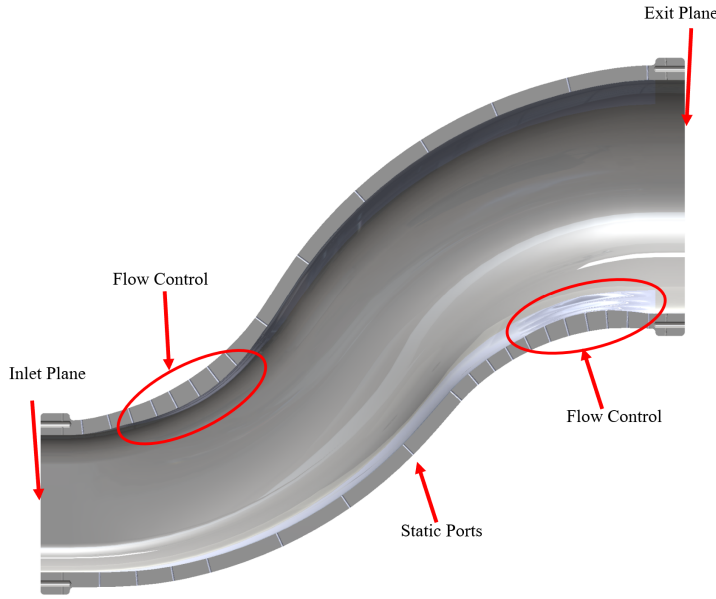


FIGURE 2: S-duct with details showing flow control regions

When automating the mesh generation process, four steps were created with the first three effected through a *Python* 3.8 script (Figure 3). The overarching *Python* script, henceforth known as the *automation script*, opened the individual programs and began the scripts or macros needed for that stage.

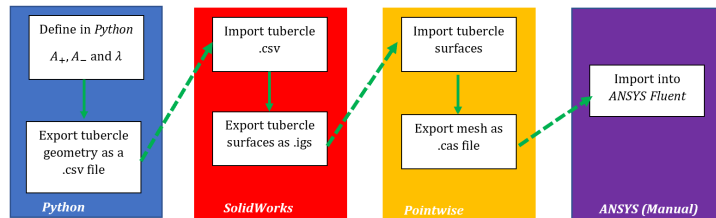


FIGURE 3: Automation process used to create the input mesh file for *ANSYS Fluent*

The *Python* script mentioned in Figure 3 is only used to generate the tubercle profile, henceforth known as the *profile script*. The profile script received three key tubercle parameters as input: positive amplitude (A_+), negative amplitude (A_-), and wavelength (λ). The amplitudes are measured with respect to the line which splits the sinusoidal

pattern to ensure equal areas on both sides. Once the sinusoidal pattern was created, it was overlaid onto the existing S-duct profile for the tubercle locations. Figure 4 shows the three planes used for both inner radii.

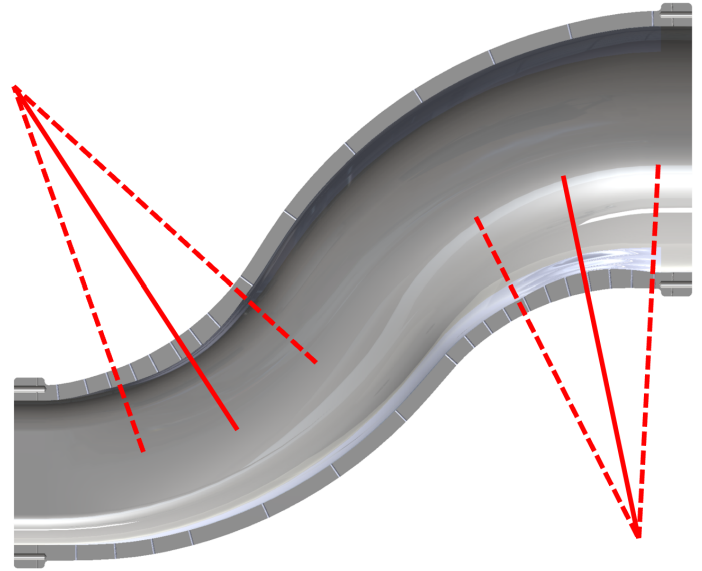


FIGURE 4: Baseline S-duct surface loft

The dashed lines in Figure 4 are the starts and ends of the tubercle profile. The solid lines depict the fully developed tubercle locations. The dashed planes mark the limits of any tubercle design, upstream and downstream the S-duct will be identical and there is a smooth transition occurred between the existing baseline duct and the new geometry. For both inner radii there is a circumferential extent of the tubercles to keep the depth into the page of Figure 4 constant. Figure 5 shows the three key parameters on the tubercle profile for the rectangular inner radius of the S-duct.

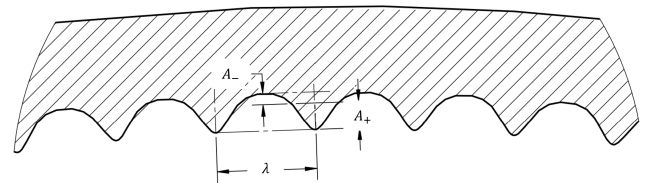


FIGURE 5: Tubercle design parameters

Once the profile was created, it is exported as a *csv* file to be used in *SolidWorks 2019*. The automation script opened *SolidWorks* and began the designed macro, that imported the tubercle profile to the set plane, shown in Figure 4, then lofted the inner surface. Figure 6 depicts the baseline S-duct inner surface and Figure 7 demonstrates the tubercle lofted sections, with the rectangular inlet located on the left, and round outlet on the right. The lofted tubercle sections were exported as an *igs* file for the next step.

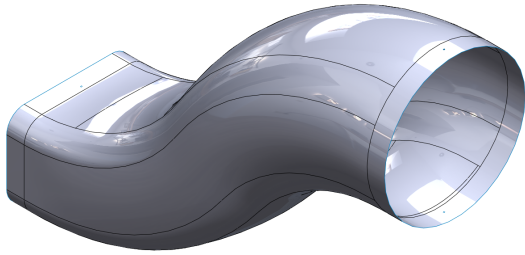


FIGURE 6: Baseline S-duct surface loft

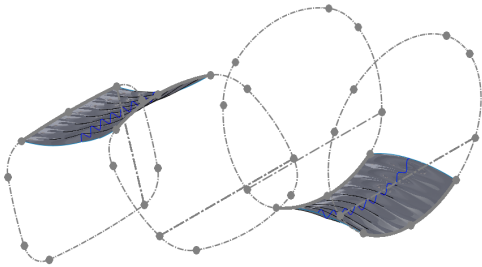


FIGURE 7: Tubercle lofted surface of the FC4 duct

The meshing process was done manually for the baseline duct then the new tubercle surfaces were overlaid. The baseline S-duct mesh used *Pointwise 18.4* with an unstructured mesh of over 17×10^6 cells. In previous work by Hancock [17], Hickling [13] and others; 8×10^6 cells were used successfully for the half S-duct model, therefore the

17×10^6 used for the full model are considered sufficient. The wall layers were refined using a *TReX* mesh with a growth rate of 1.3 and maximum number of layers of 25, making a structured mesh in this region, to be able to predict the complexity of the boundary layer flow.

The tubercle sections were imported by the automation script which ran a *glyph* script in *Pointwise*. The new inner radii were located in the correct orientation and the existing mesh was projected onto the new surface. The surface and volume mesh was then re-initialized and exported to be used in the CFD software. The tubercles are not possible to discern in the mesh but, the baseline S-duct is presented in Figure 8 to show the boundary conditions.

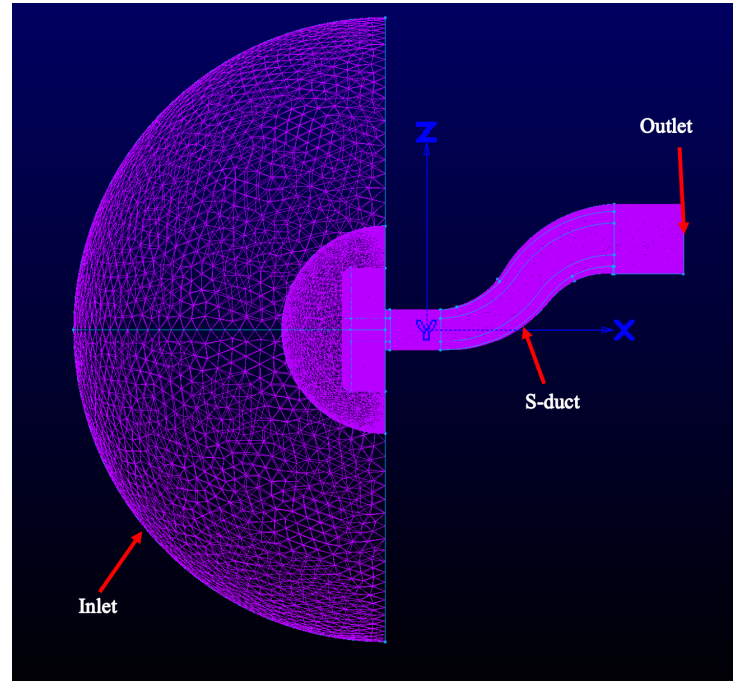


FIGURE 8: Baseline S-duct surface mesh with boundary conditions

RESULTS AND DISCUSSION

The mesh was validated by checking the aspect and volume ratios which, for the majority of cells, was in a reasonable range, falling below 10 and 10 respectively. Figures 9 and 10 depict these two parameters for the tubercle S-duct.

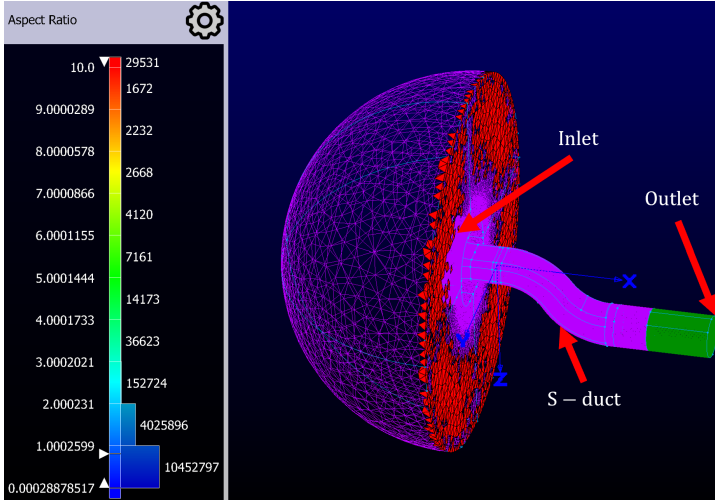


FIGURE 9: Baseline S-duct aspect ratio for a given cell

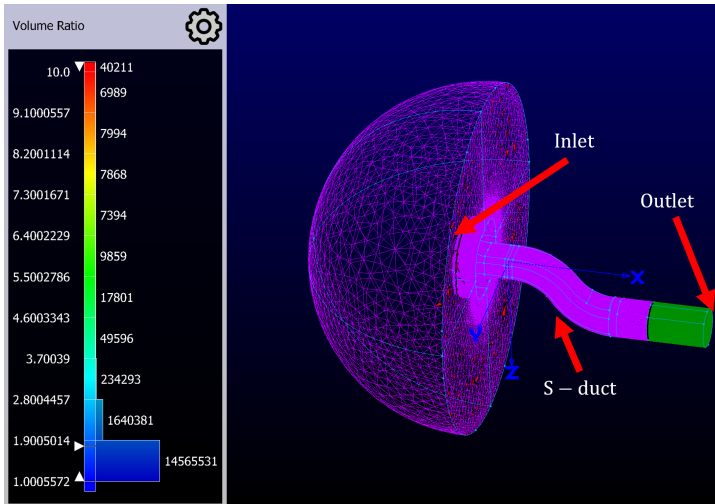


FIGURE 10: Baseline S-duct volume ratio between cells

CONCLUSIONS AND RECOMMENDATIONS

The baseline S-duct was numerically modeled and is presented in Rider [16]. The tubercled S-duct was also modeled but at a different Mach number. Both models were able to converge which validates that this method of tubercle modifying automation is able to create a mesh based on the three key tubercle parameters within a reasonable range.

It is recommended that in future work the CFD be included in the automation and eventually an optimization scheme can be created.

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