10th ANKARA INTERNATIONAL AEROSPACE CONFERENCE **AIAC-2019-078**
18-20 September 2019 - METU, Ankara TURKEY

NUMERICAL AEROACOUSTICS INVESTIGATION OF THE EFFECT OF ROTOR TRAILING EDGE SERRATIONS ON TONAL NOISE OF A TRANSONIC COMPRESSOR STAGE

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ABSTRACT

This study illustrates the computational aeroacoustics calculations to investigate the effect of the rotor trailing edge serrations on tonal noise generation of a transonic compressor stage. Dominant sources of the interaction tonal noise in axial compressor applications are potential field and rotor wake-stator vane interactions. The physics of the latter is based on the periodical impingement of the rotor wakes on stator vane which generates unsteady pressure fluctuations on stator vane surface, eventually tonal noise generation. Modifying rotor trailing edge with serrations enhance the mixing in the rotor wake and reduce the momentum deficit in rotor wakes. NASA Stage 37 test case was selected as the investigated transonic axial compressor stage. 4 different configurations of the rotor trailing edge design were tested with computational fluid dynamics tool Star CCM+. Effect of serrations on rotor wake were investigated with steady state Reynolds Averaged Navier Stokes simulations, while unsteady RANS (URANS) simulations were carried out to calculate the tonal noise. Near-field acoustics directly computed from URANS simulation, whilst, for the far field calculations, Ffowcs Williams and Hawkings (FW-H) acoustic analogy solver was utilized. Steady state analysis showed that serrations have a considerable effect on the flow field which modifies the wake by reducing it. Time-dependent flow field was investigated by unsteady CFD analyses for normal and serrated rotor configurations. It was observed that, the serrations are effective way to reduce the unsteady pressure fluctuations on stator vane and decrease the noise generation of compressor stage.

INTRODUCTION

In multi-stage axial compressor applications, impingement of the rotor blade creates unsteady periodic pressure fluctuations on stator vane which is a very efficient source of tonal noise generation. The width and the area of the rotor wake are determinant features of the wake on amplitude of the tonal noise. As the rotor wake becomes stronger and thicker, the amplitude of the unsteady pressure fluctuations on stator vane surface increases. This can be explained via the upwash velocity phenomena. Since the rotor wake is a momentum deficit within the free stream between the two rotor blades, the velocity triangles for the free stream and the wake differs each other. As seen in Figure 1, due to the momentum deficit the relative velocity of the wake centerline is smaller than the free stream relative velocity. Since the blade speed

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is same for both triangles the upwash velocity arises between the absolute velocities of free stream and the wake regions. This velocity component, which is shown with green arrow, is the normal component of velocity which impinges on stator vane surface. If the wake is stronger the upwash velocity increases and the amplitude of the pressure fluctuations on stator vane surface are higher. The magnitude of the upwash velocity arising on the stator vane varies between zero and its higher value at blade passing frequency (BPF). During the motion of the rotor blade, if the free stream flow impinges on stator vane upwash velocity becomes zero. However, when the rotor wake hits the stator leading edge upwash velocity raises up to its maximum value. This is the main tonal noise generation mechanism of the rotor-wake stator vane.

Rotor serrated trailing edge modifications are proposed to enhance the mixing of the flow between the pressure side and suction side to reduce the strength of the rotor wake without altering the aerodynamic performance of the compressor stage. This technology is also utilized in commercial airplane turbofan engine nacelles to increase the mixing between hot and cold flows. This application is names as chevrons and provides a noise reduction with an aerodynamic loss penalty.

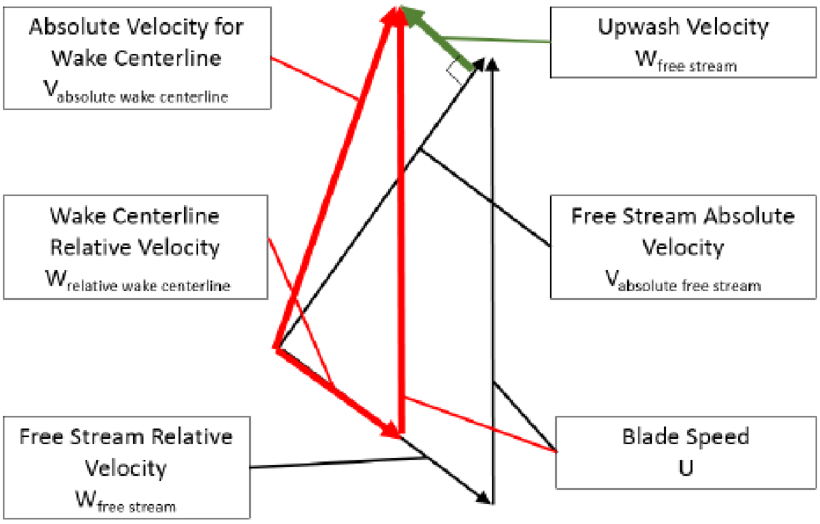

Figure 1: Upwash velocity

It is claimed that the serrations at the trailing edge of the rotor reduces the wake strength by enhancing mixing for an coutner-rotating open rotor engine [Weckmuller and Guerin, 2012]. As seen in Figure 2, they stated that serrations at the front rotor engine modifies the wake with mixing process.

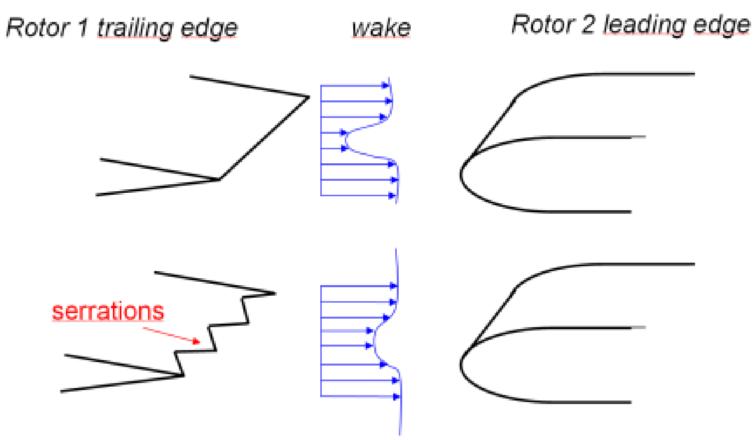

Figure 2: Serrations effect on rotor wake.

They tested 4 different configurations as seen in Figure 3 and the preliminary results showed 2 dB noise reduction.

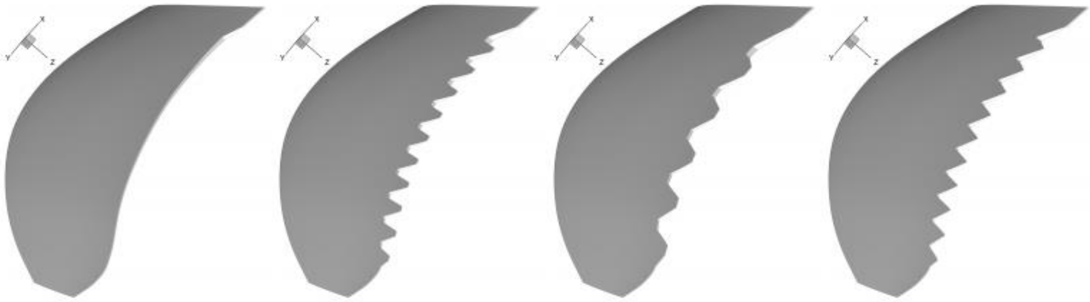

Figure 3: Different serrated trailing edge configurations [Weckmuller and Guerin, 2012]

In an another study an hybrid approach with steady state RANS simulation and analytical calculations were resorted to optimize the serrated trailing edge geometries on a counter-rotating open rotor. They claimed that the optimized serration geometry provides 1 dB noise reduction without aerodynamic performacne loss [Jaron, Moreau, Guerin and Schnell, 2016].

METHOD

Steady State CFD Simulations

In order to investigate the effect of the rotor serrated trailing edge on tonal noise, 4 different configurations of serrations were created. Configuration 1 has semi circular structure, the other ones has triangle shape. Configuration 2 has the same geometrical shape configuration 4, however number of serrations are higher in configuration 4. Finally, configuration 3 has bigger serrations than the second one as shown in Figure 4.

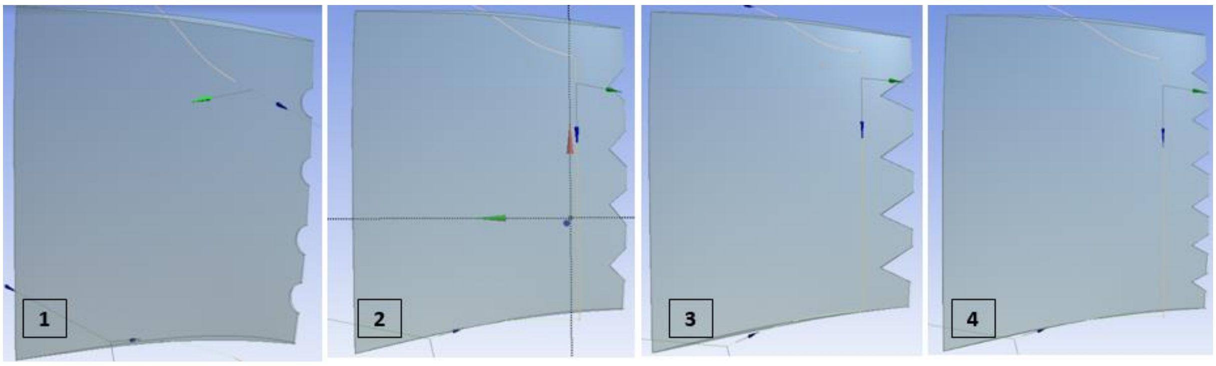

Figure 4: Different rotor serrated trailing edge configurations

In the first step, steady state computational fluid dynamics analysis of the original configuration, serrated configuration 1,2,3 and 4 were respectively conducted in order to see how the serrations affect the rotor wake. CFD domain is modeled in Star CCM+ as seen in Figure 5. Only one rotor and stator blade were imported in model and the periodic boundary conditions were utilized.Rotation of the rotor blade is modeled with rotating reference frame and mixing plane interfaces were utilized for connecting stationary and rotating domains. Other simulation details and boundary conditions are show in Figure 6.

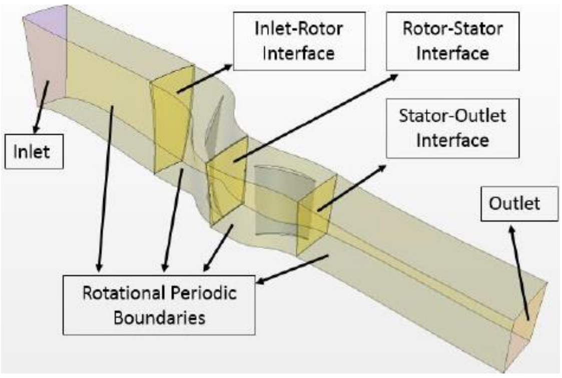

Figure 5: CFD domain and boundary conditions of compressor stage

RANS Simulation Numerical Model Details	
Solver	Implicit Coupled Solver
Rotation Modeling	Rotating Reference Frame
Rotational Speed	17188.7 rpm
Inlet Absolute Total Pressure	101325 Pa
Inlet Total Temperature	288.15 K
Outlet Absolute Static Pressure	120000 Pa
Turbulence Model	SST k-ω

Figure 6: Steady state simulations modeling specifications and boundary conditions

Meshing

Meshing process of serrations is quite more difficult than meshing a normal rotor blade, since the geometry topology varies at each span from hub to tip as seen in Figure 7. Normally 10-15 elements are sufficient from hub to tip, however for the serrated configurations this rises up to 100-120 elements which dramatically increases the number of elements in rotor domain. Normal rotor geometry was meshed with 1,250,000 elements. However over 3,500,000 elements was created for the serrated rotor geometries.

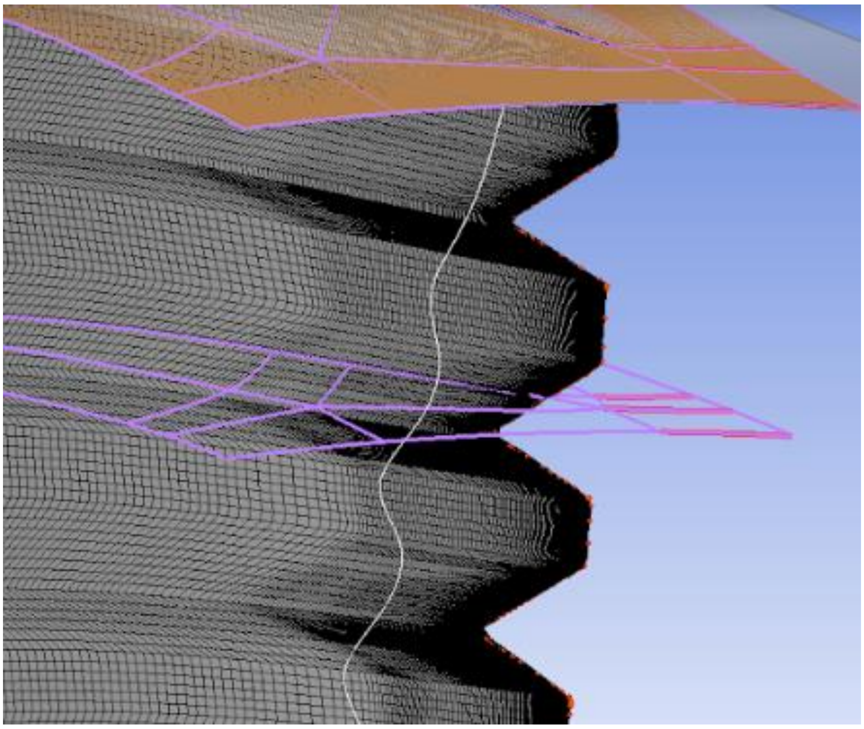

Figure 7: Serrated trailing edge rotor domain mesh

Transient CFD Simulations

In Star CCM+ computational fluid dynamics calculations were conducted for each case by solving URANS equations. URANS method was resorted instead of LES based turbulence models since URANS models can be prefferred when flow features are certainly tonal like blade passing frequency [Holewa and Lesnik and Ashcroft and Guerin, 2017]. Moreover, significant amount of computational time is saved when solving URANS instead of LES.

Figure 8 shows the modeling specifications and the boundary conditions of the transient CFD simulations. The computational fluid dynamics model consist of extended stationary inlet, rotating rotor, stationary stator and extended outlet domains. Periodic boundary conditions were utilized one each side in order to represent full wheel. Rigid body motion method was applied to simulate the motion of the rotor blade. Unsteady implicit coupled solver was selected with the time step of $9.696x10^{-7}$ s which corresponds to 0.1° rotation of rotor blades in tangential direction. This means rotor blade completes one blade passing with 100 time steps

URANS Simulation Numerical Model Details	
Solver	Unsteady Implicit Coupled Solver
Rotation Modeling	Rigid Body Motion
Material	Air Ideal Gas
Time Step Size	$9.696x10^{-7}$ s
Rotational Speed	17188.7 rpm
Inlet Absolute Total Pressure	101325 Pa
Inlet Total Temperature	288.15 K
Outlet Absolute Static Pressure	145000 Pa
Turbulence Model	SST k-ω

Figure 8: Transient simulations modeling specifications and boundary conditions

RESULTS

Steady State Simulations

Steady state analysis according to the conditions which are mentioned above were completed. The results showed that serrated trailing edge have an observable effect on modifying the rotor wake. A plane section was defined between the rotor and stator in order to visualize the rotor wake from hub to tip. Relative Mach number contours are plotted on this plane sections and the comparisons are illustrated in Figure 9, Figure 10, Figure 11 and Figure 12. As seen minimum modification was achieved with configuraion 1. That means, triangle serration is more effective than the semi circle serration to modify the rotor wake. Moreover, as the size and the number of the serration increases, the modification on rotor wake increases as well. It can be observed that the most obvious rotor wake modification was achieved by configuration 3 and configuration 4.

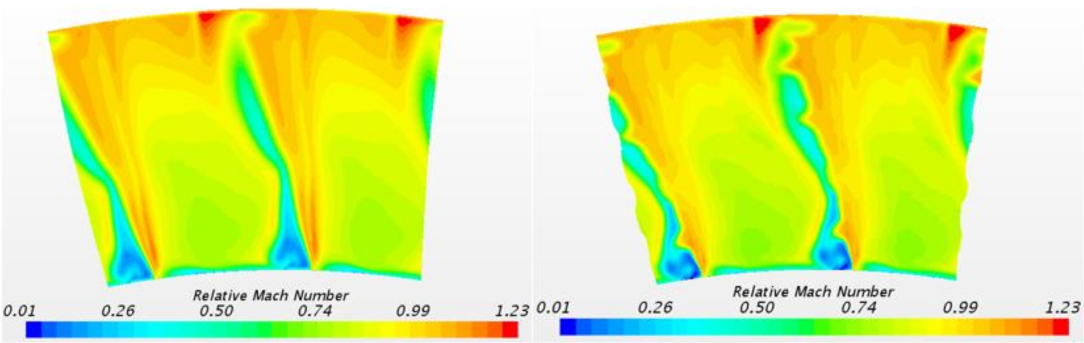

Figure 9: Original rotor (left) and serrated rotor conf.1 (right) relative Mach number contours

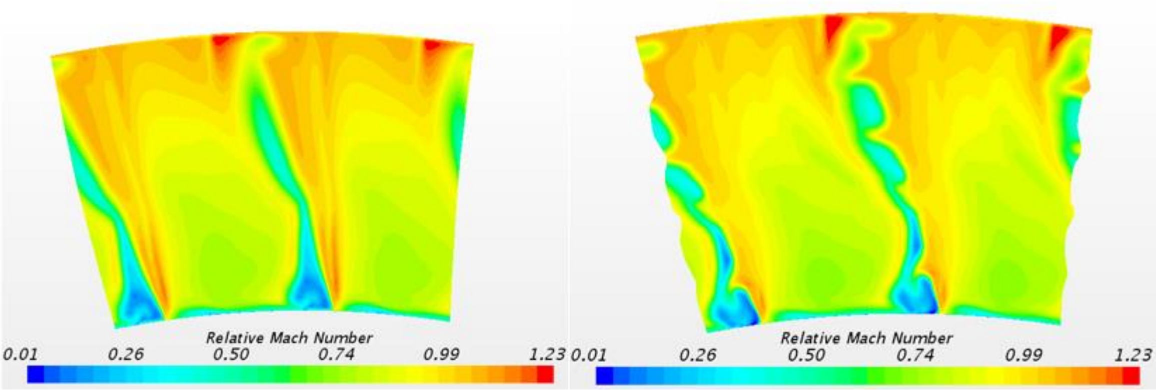

Figure 10: Original rotor (left) and serrated rotor conf.2 (right) relative Mach number contours

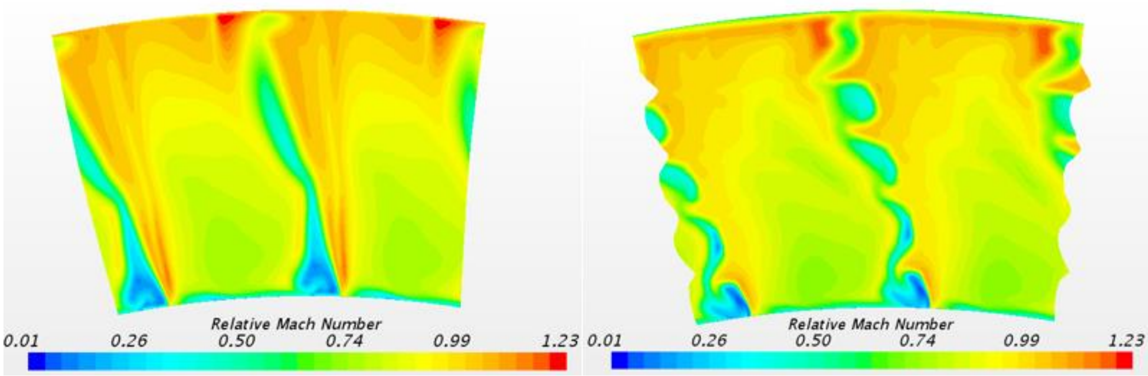

Figure 11: Original rotor (left) and serrated rotor conf.3(right) relative Mach number contours

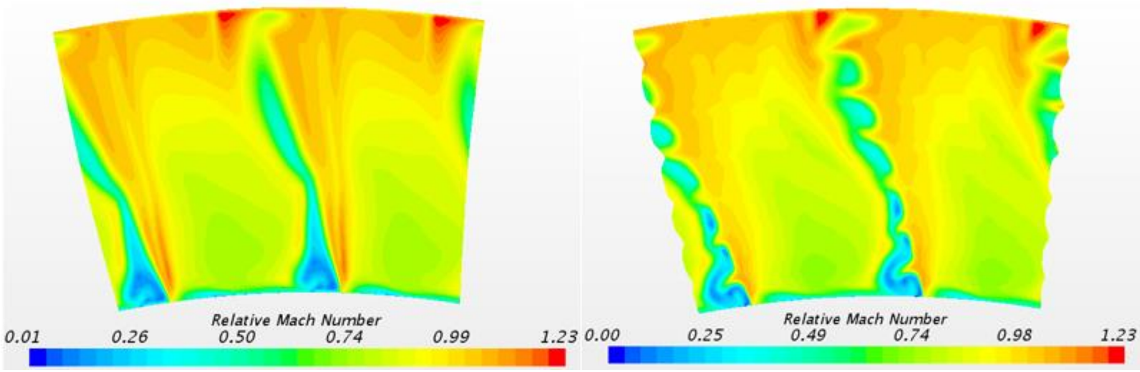

Figure 12: Original rotor (left) and serrated rotor conf.4(right) relative Mach number contours

Transient Simulations

In this study transient simulation was conducted only for original configuration and configuration 3 since configuration 3 provided the best promising modification in steady state simulations. Figure 13 shows how the serration of configuration 3 modifies the rotor wake at 75% span.

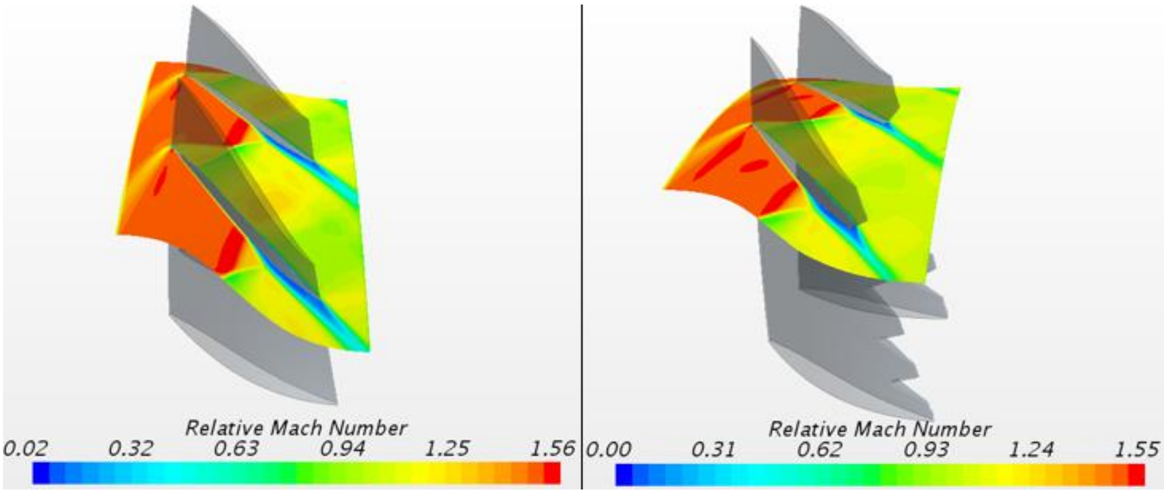

Figure 13: Original rotor (left) and serrated rotor conf.3(right) relative Mach number contours at 75% span

In order to investigate the transient flow field, 4 pressure probes were located near the stator blade as shown in Figure 14. These probes were used to compare the amplitude of pressure fluctuations for original configuration and configuration 3. Moreover, the measured pressure signal on these probes were used to calculate the sound pressure level in terms of dB to observe the effect of serrations on near-field noise generation.

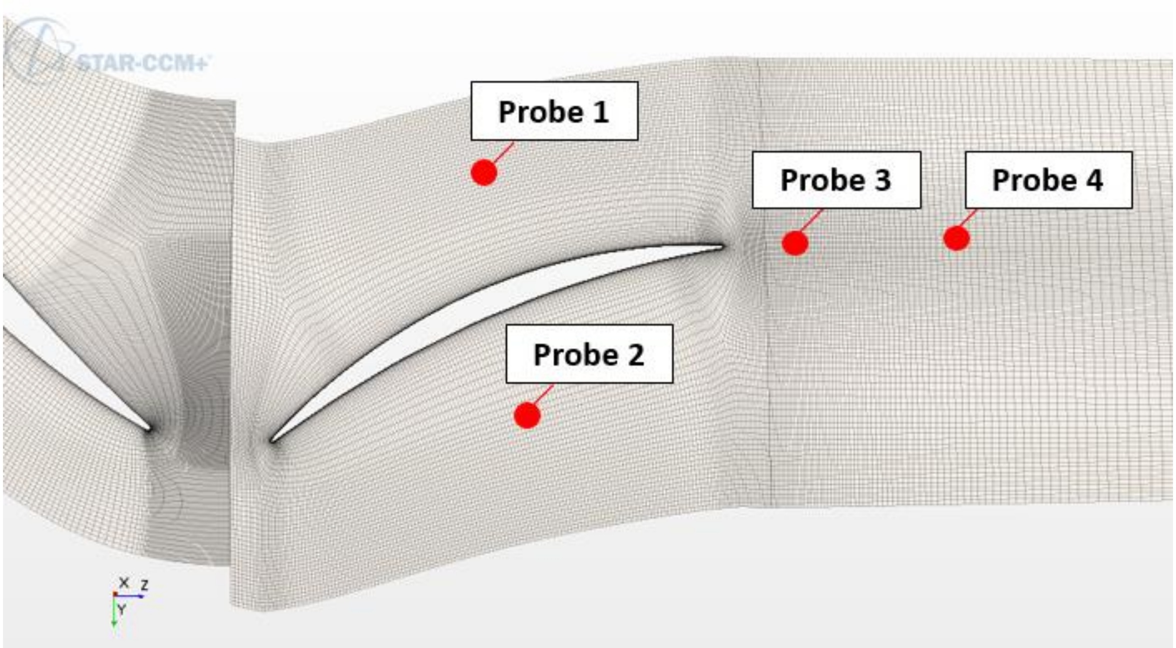

Figure 14: Pressure probes near stator blade

Transient pressure signal obtained by the probe 1 is illustrated in Figure 15. As seen the amplitude of the pressure signal is reduced by introducing serrations. This reduction in the pressure signal amplitude provides a noise reduction as seen in Figure 16. Either tonal noise or broadband noise which is measured at probe 2 is lower for the serrated trailing edge rotor design.

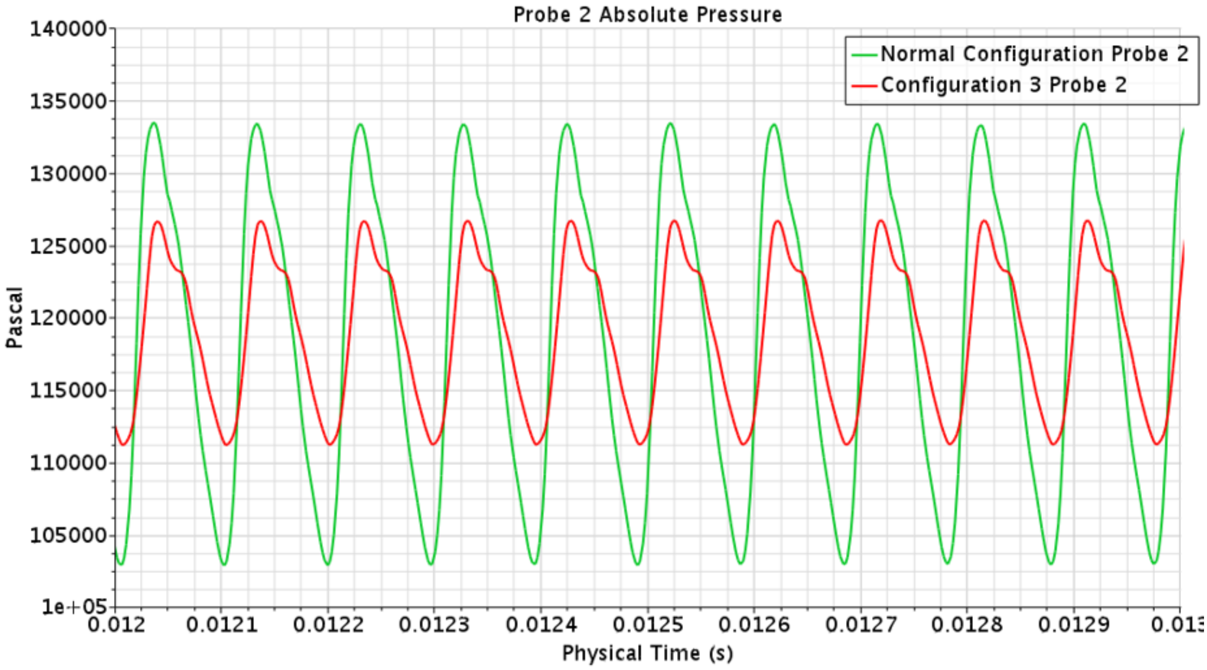

Figure 15: Transient pressure data at probe 2

First three blade passing frequency noise values which are measured at shown pressure probes are tabulated in Table 1. As seen serrated rotor blade design has a substantial effect on reducing tonal noise values. A noise reduction of 5 to 8 dB is observable fort he first three tones.

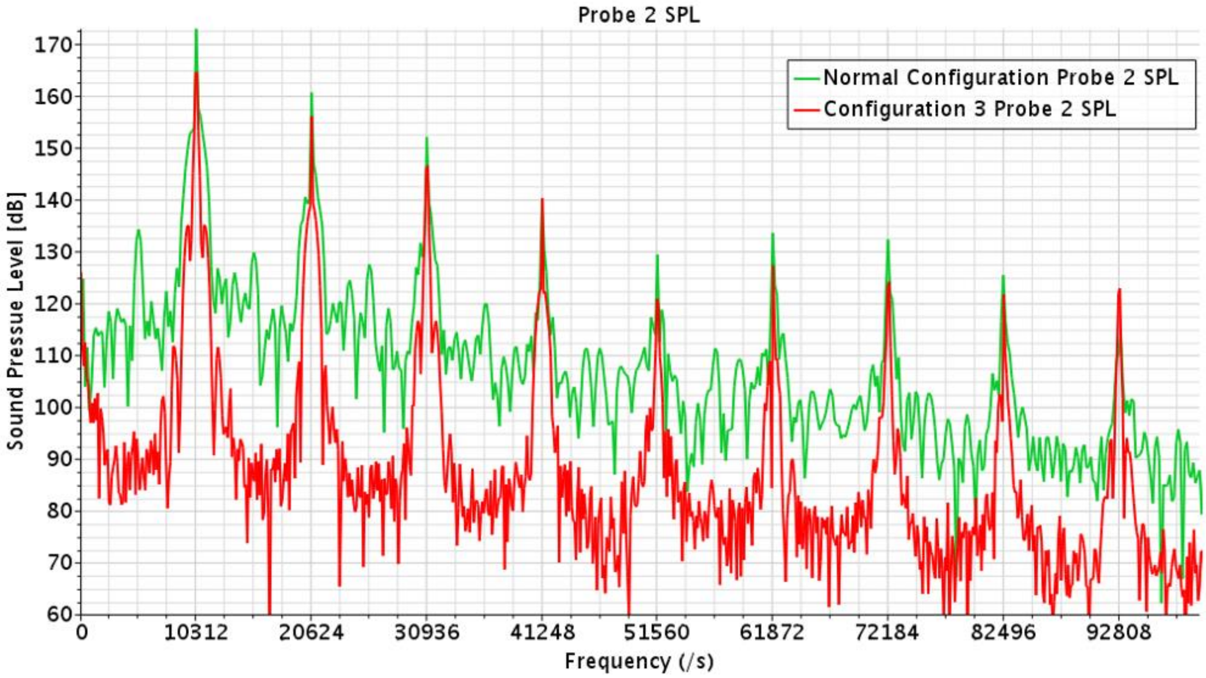

Figure 16: Probe 2 sound pressure level [dB] data

Probe	Configuration	Tone 1	Tone 2	Tone 3
Probe 1	Normal	159	149	141
	Serrated	152	144	137
Probe 2	Normal	172	161	153
	Serrated	165	156	147
Probe 3	Normal	170	155	153
	Serrated	165	155	145
Probe 4	Normal	168	145	149
	Serrated	162	144	142

Table 1 : Tonal noise values [dB] at near-field probes

In order to investigate the noise reduction mechanism, Mach number probes are located in the wake regions of the rotor blades for each case as shown in Figure 17. As seen, to observe the effect of the serrations on rotor wake modification, 4 probe are located downstreams of the each serration at different spans. Serrations are expected to reduce the momentum deficit in the rotor wake as illustrated in Figure 2.

As seen in Figure 18, rotor wake is modified by the serration at Mach number probe 4. The deficit in the momentum is reduced by introducing serration on rotor trailing edge. As mentioned, this decreases the magnitude of the upwash velocity in the rotor wake which result in smaller pressure fluctuations on stator surface.

The pressure fluctuation on the stator surface is monitored by locating 4 pressure probes on the trailing edge of stator vane as seen in Figure 19. These probes are located on the same alignment as the rotor trailing edge serrations in order to capture the effect of the modified wake on pressure field. This effect is visualized at probe 4 as seen in Figure 20. The magnitude of the pressure fluctuation on stator vane is reduced by serrations.

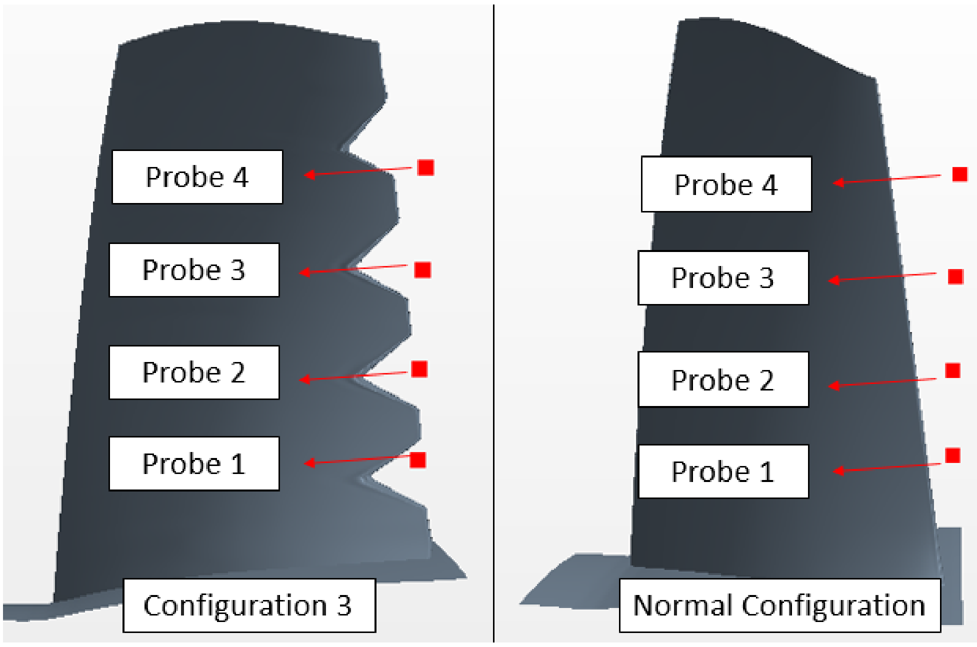

Figure 17: Mach number probes

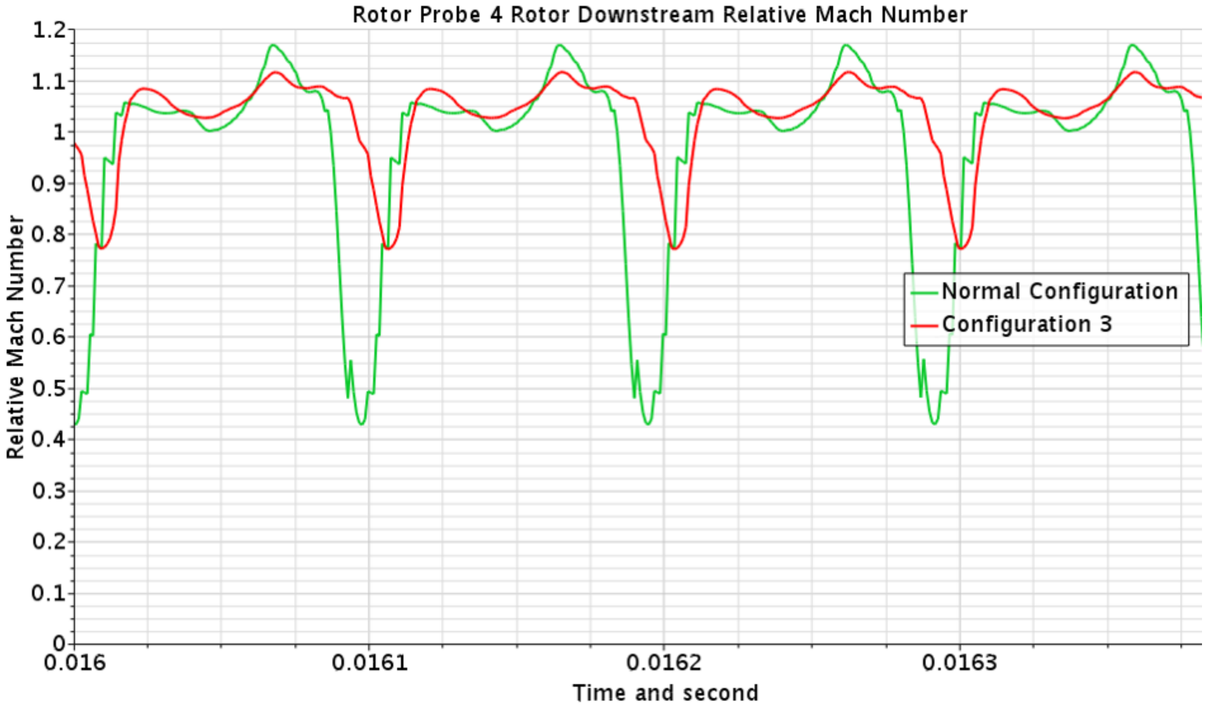

Figure 18: Rotor wake Mach number at probe 4

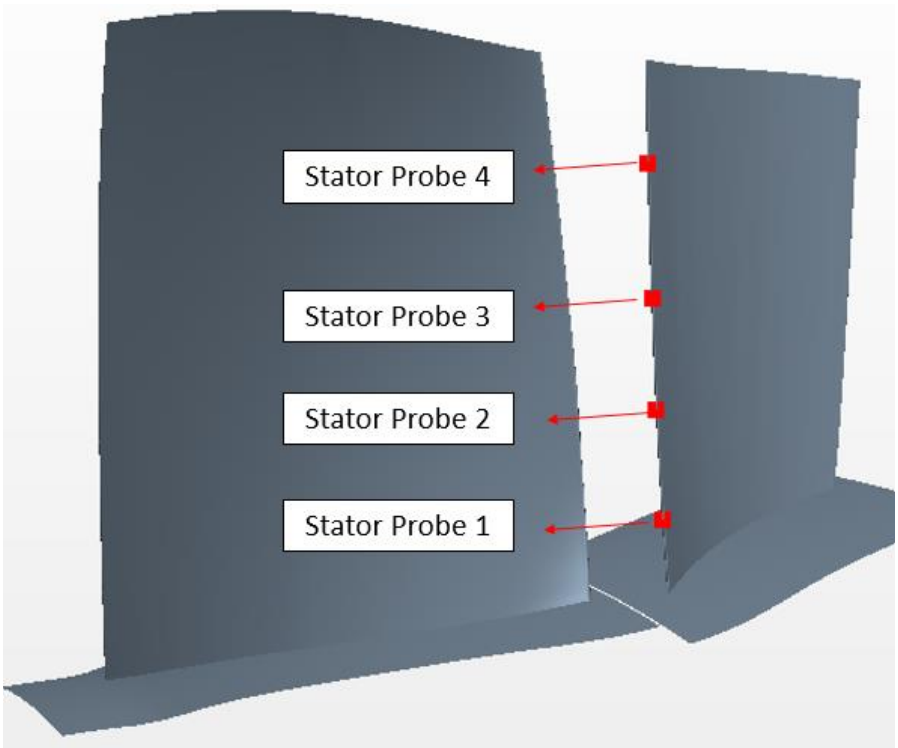

Figure 19: Stator surface pressure probes

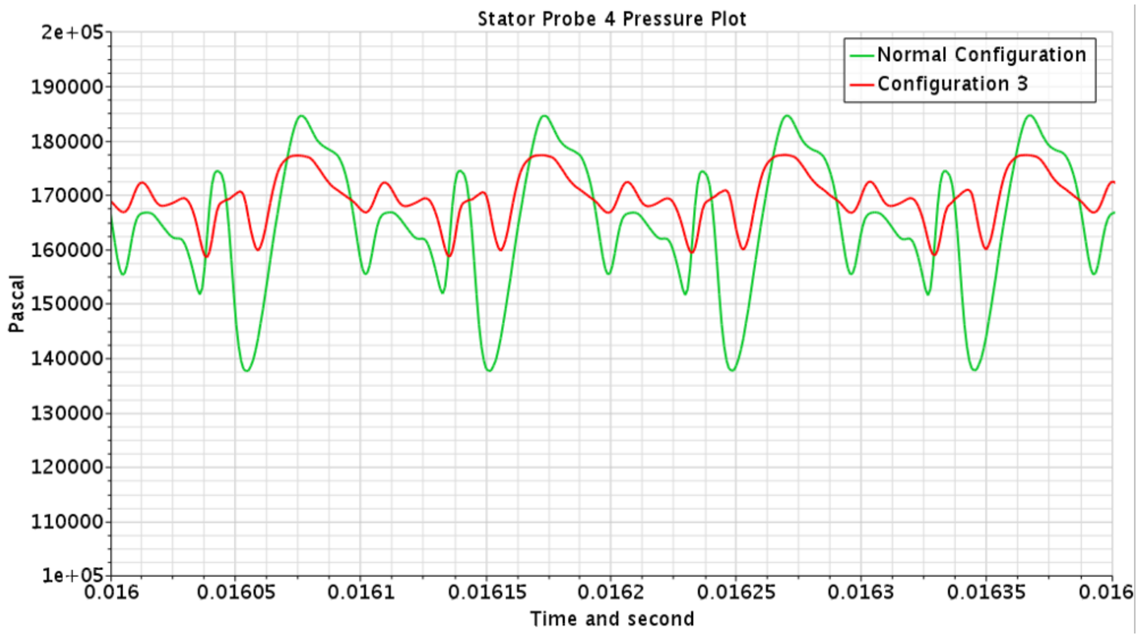

Figure 20: Transient pressure data at probe 4

Far-Field Acoustics

Far-field aeroacoustics analysis is conducted by locating three far-field FW-H receivers out of the CFD domain. Recorded transient surface pressure data of stator vane is used as source term for FW-H equations. The noise is propogated from this source term to the receivers which are shown in Figure 21.

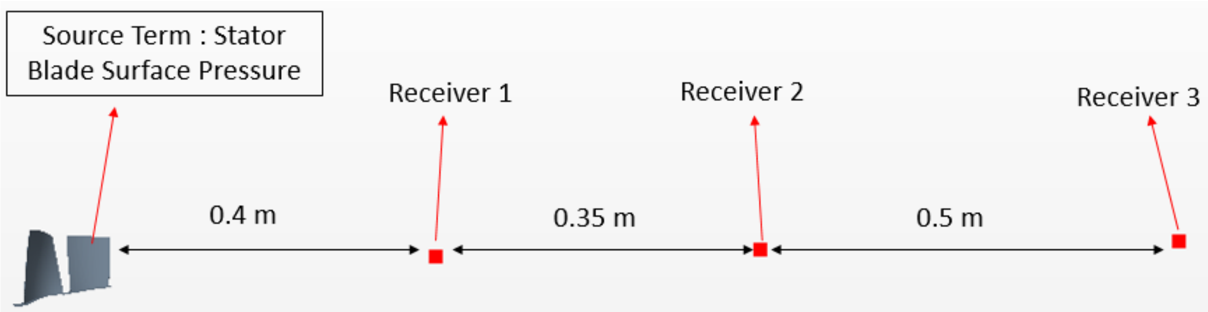

Figure 21: FW-H receiver locations

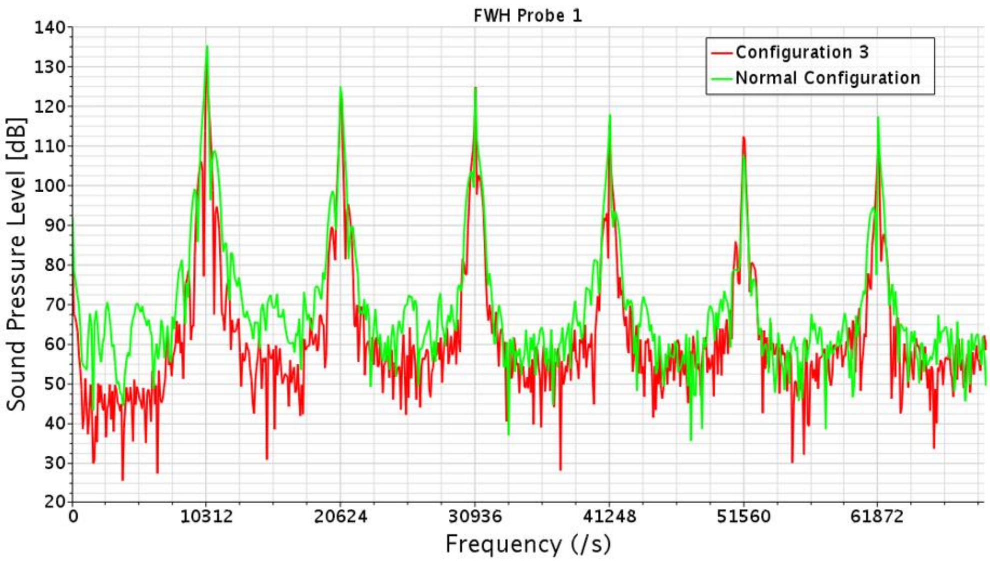

Figure 22: FW-H receiver 1 sound pressure level [dB]

Figure 22 demonstrates the sound pressure level in terms of dB on first six blade passing frequency tones for normal and serrated rotor configurations. As seen, the tonal noise and broadband noise values are higher for the normal rotor configuration.

Receiver	Configuration	Tone 1	Tone 2	Tone 3
Receiver 1	Normal	135	125	124
	Serrated	131	122	124
Receiver 2	Normal	130	119	118
	Serrated	126	117	119
Receiver 3	Normal	125	115	114
	Serrated	121	113	114

Table 2 : Tonal noise values [dB] at far-field receivers

Tonal noise values obtained in far-field receivers proves that serrations are effective method to reduce the tonal noise as seen in Table 2.

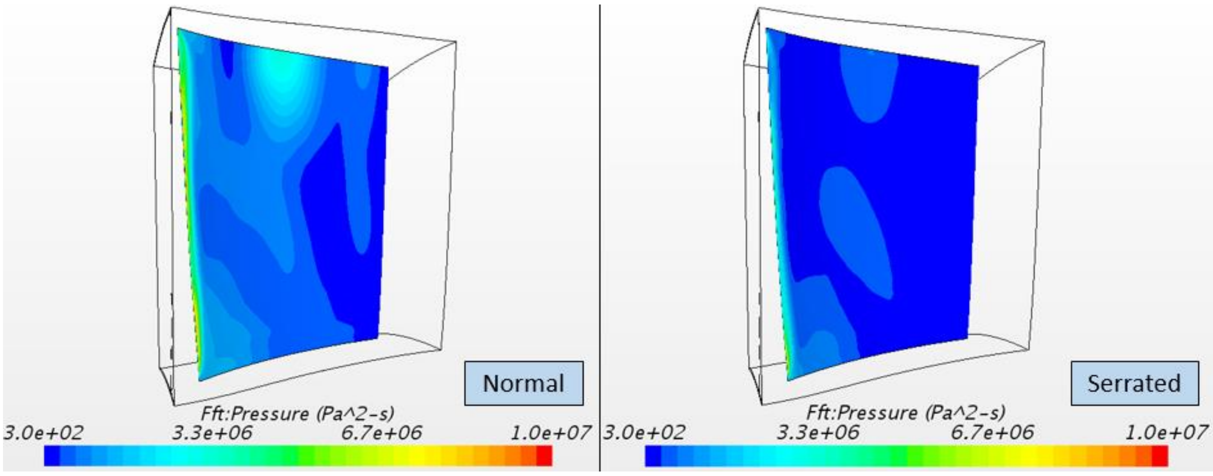

Figure 23: Pressure fluctuation energy on stator surface

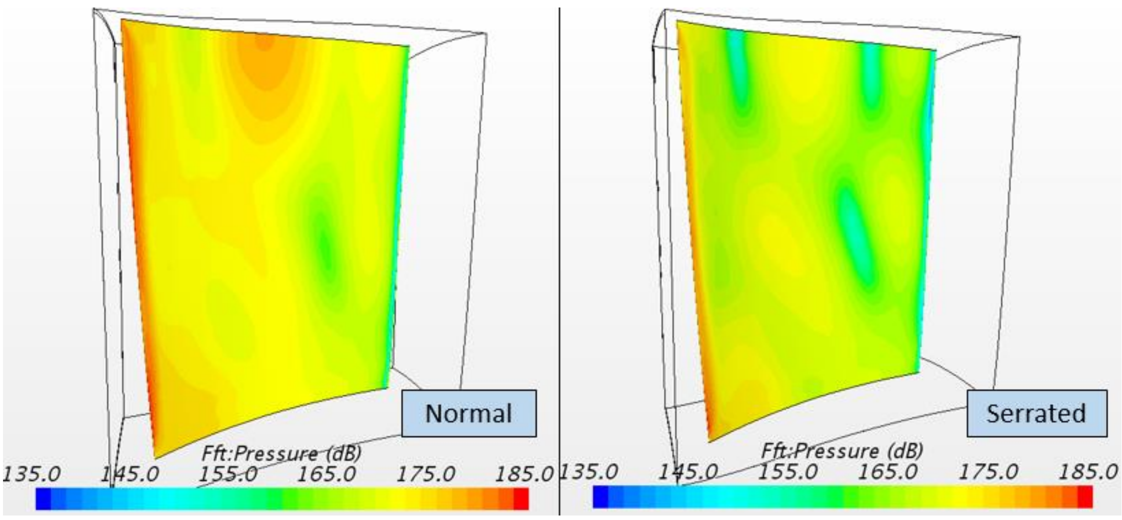

Figure 24: Noise source on stator surface [dB]

Figure 24 illustrates the pressure fluctuation energy comparison on stator vanes for each configuration. It is observable that the energy of the fluctuations are higher for the normal configuration.

The comparison of the noise sources at 1st BPF on the stator vanes of normal and serrated configurations is shown in Figure 24. As seen, since the pressure fluctuations is less for serrated configuration, the noise source on the stator vane of serrated design becomes smaller compared to normal configuration.

Aerodynamics

In order to investigate the effect of the rotor trailing edge serrations on the aerdoynamic performance, total pressure ratio of the compressor stage for normal and serrated designs are plotted as seen in Figure 25. The total pressure ratio for serrated design is slightly lower than the normal configuration. This means, serrations do not distract the flow field and maintain the same aerodynamic performance.

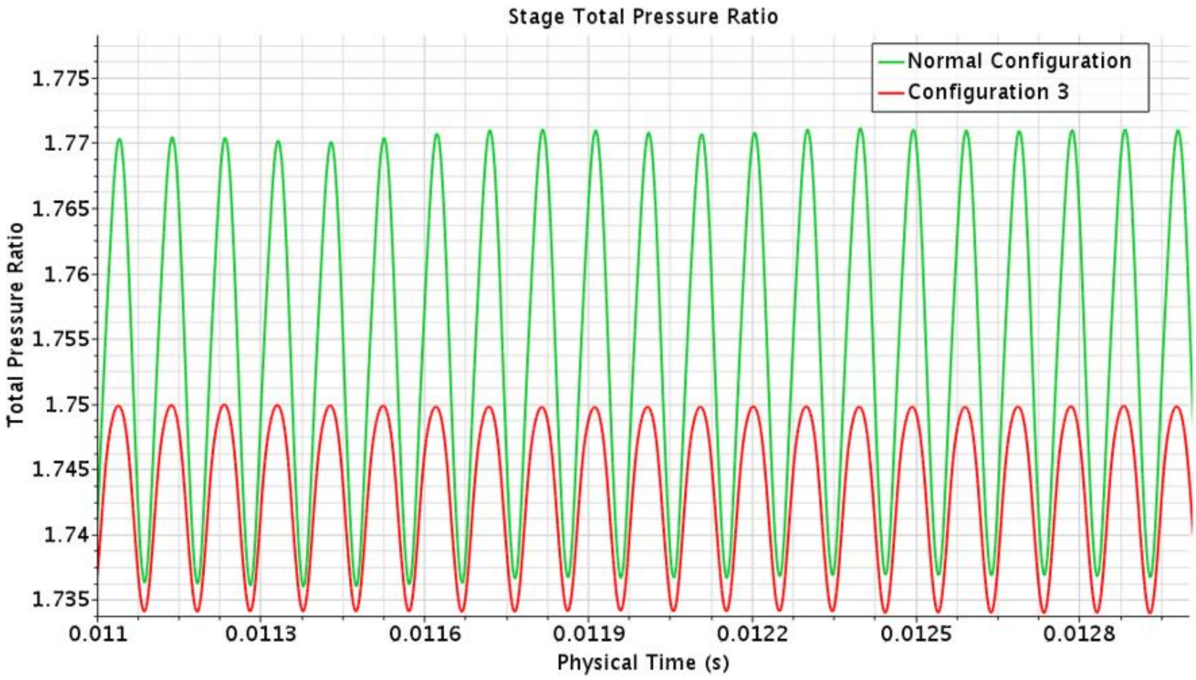

Figure 25: Stage total pressure ratio

CONCLUSIONS

Steady-state CFD simulations illustrate that the rotor wake can be modified by introducing serrations on rotor trailing edge. Since the serration configuration 3 showed the best promising result for rotor wake reduction, the aeroacoustics calculations were carried out with normal configuration and configuration 3. Near-field acoustic analyses were done by calculating pressure waves near the noise source which is the stator blade. Far- field calculations were conducted by using FW-H equations with the input of transient surface pressure data of stator. Near-field and far-field aeroacoustics analyses show that rotor trailing serrated edge design is an effective way to reduce the noise of the compressor stage without even disrupt the aerodynamic performance of the compressor stage. Modifying the rotor wake using the serrations resulted in lower pressure fluctuations on stator surface which generates less noise than the normal rotor configuration. Sound pressure level in terms of dB at BPF and higher harmonics are substantially mitigated as seen in the noise spectrums. Moreover, slight decrease in broad-band noise is observable.

In addition to the aerdoynamic investigation of the serrations, structural analyses must be carried out to validate the serration design, since the serrations may generate additional stresses on rotor blade.

References

Holewa, A., Lesnik, S., Ashcroft, G., & Guerin, S. (2017). CFD-Based Investigation of Turbine Tonal Noise Induces by Steady Hot Streaks. *International Journal of Turbomachinery, Propulsion and Power, 2*(1), 3.

Jaron, R. & Moreau, A. & Guerin, S. & Schnell, R. (2016) *Optimization of Trailing-Edge Serrations to Reduce Open-Rotor Tonal Interaction Noise,* International Symposium on Transport Phenomena and Dynamics of Rotating Machinery, Hawaii, 2016

Weckmuller, C & Guerin, S. (2012) *On the Influence of Trailing-Edge Serrations on Open-Rotor Tonal Noise*, 18th AIAA/CEAS Aeroacoustics Conference, Colorado, 2012