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ACOUSTIC EXCITATION AS A FLOW CONTROL TECHNIQUE IN A HIGH-SPEED COMPRESSOR CASCADE

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ABSTRACT

A numerical investigation of the effectiveness of acoustic excitation is carried out to control flow separation in a NACA65-K48 linear compressor cascade (LCC) in the absence of cascade endwalls. The operating conditions for the LCC are $Ma = 0.67$ and $Re_c = 560 \times 10^3$, which are representative of an aeroengine. For the numerical investigations, Improved Delayed Detached Eddy Simulation (IDDES) is used due to its capability to capture flow separation and unsteady flow characteristics with reasonable computational requirements among the high fidelity approaches. The flow through the cascade passage does not experience any separation at the aerodynamic design point (ADP) of the cascade. Therefore, an incidence angle of $i = 8^\circ$ is used in this study where flow separation is observed over blade the suction surface at $x/c \approx 0.6$. For acoustic excitation, both external and internal acoustic excitation techniques are investigated. In external acoustic excitation, the sound source is distributed at the inlet boundary of the computational domain whereas in internal excitation, sound waves are introduced into the computational domain from a thin slot located at the onset of flow separation on the blade suction surface. Sound waves are introduced in the flow field at the modal frequencies in the uncontrolled flow, which are $St_c = 0.187, 0.409$, and 0.618 in terms of Strouhal number based on the blade chord length at a constant excitation amplitude of $SPL = 151\text{dB}$. The results have indicated that external acoustic excitation has no major effect in controlling flow separation in the LCC. Internal acoustic excitation, on the other hand, has a strong effect in modulating the flow separation in the LCC passage such that a reduction of $\Delta\zeta_{max} \approx 16\%$ is observed in the total pressure loss coefficient on the measurement plane located $0.4C_{ax}$ downstream of the cascade exit. Further investigations are also carried out for the effect of sound amplitude on the effectiveness of internal acoustic excitation. In overall, acoustic excitation can serve as a means of flow control in aeroengine compressor cascades.

Keywords: Flow control, acoustic excitation, compressor cascade

NOMENCLATURE

C	chord length
Δt	numerical time step
f	frequency
h	blade height
i	incidence angle
t	pitch length
τ	$t(U_\infty/c)$, convective time
ν	Kinematic viscosity [$\text{m}^2 \text{s}^{-1}$]
ζ	Total pressure loss coefficient, $\frac{P_{t,in} - P_t}{P_{t,in} - P_{in}}$
Re_c	Reynolds number based on chord length, $U_\infty c / \nu$
St	Strouhal number, fc/U_∞
ADP	Aerodynamic Design Point
IDDES	Improved Delayed Detached Eddy Simulation
LCC	Linear Compressor Cascade
SPL	Sound Pressure Level [dB]

Superscripts and subscripts

ax	axial
exc	excitation
t	pitch-averaged
∞	freestream value

1. INTRODUCTION

The current trend in the design of axial compressor blades in modern aeroengines is to increase the blade aerodynamic loading to reduce the number of blades/stages, and hence, the weight of the aeroengine. Although higher aerodynamic loading can help in reducing the overall weight, the main drawback is an increase in the adverse pressure gradient across a stage that could trigger flow separation. Flow separation results in increased cascade blockage and reduced aerodynamic performance. Hence, it is detrimental to compressor stability and performance. Therefore, control of flow separation is critical in the design of modern axial compressors [1–3].

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Unlike other flow control techniques, acoustic excitation aims to excite the instabilities already present in the uncontrolled flow, and hence, requiring a considerably lower energy input. The working mechanism of acoustic excitation is to amplify the instabilities so that the transition-to-turbulence characteristics are altered in the flow, customarily resulting in an earlier transition. Therefore, shear layer roll-up and vortex shedding characteristics are often affected, which potentially improves the momentum transfer across the separated shear layer into the near-wall, low-momentum flow regions [1, 4–8]. Acoustic excitation can be applied in the form of external and internal excitations where the sound source is located away from the geometry of interest and in the vicinity of the separated flow, respectively. The effectiveness of acoustic excitation has been demonstrated by previous research on low to moderate subsonic flow separation control over isolated aerofoils [4, 7–9] and low-pressure turbines [10, 11].

Previous studies [1, 4, 5, 7] have shown that the dominant frequencies in the uncontrolled flow spectra are the most effective sound frequencies for acoustic excitation. Therefore, accurate prediction of flow separation characteristics plays a critical role in the investigation of flow control by acoustic excitation. The unsteady and three-dimensional nature of separated flow often requires use of high fidelity turbulence modelling approaches such as Large Eddy Simulation (LES) or Direct Numerical Simulation (DNS) as Reynolds-Averaged Navier-Stokes (RANS) equations are not capable of providing the required accuracy due to their averaging and modelling nature. The prohibitive computational cost of high fidelity models intrigued researchers and engineers to focus on hybrid models that take advantage of both high fidelity and RANS models. Detached Eddy Simulation (DES) used in the current study is a hybrid RANS/LES model that aims to utilise RANS in attached boundary layer regions to reduce the computational cost whereas it switches to an LES model in the rest of the computational domain to improve the numerical accuracy [12]. Improved Delayed DES (IDDES) is a modified DES model to cure the problems of classical DES, so called DES97, such as grid induced separation and log-layer mismatch [13]. Therefore, IDDES is considered to be appropriate for the current study.

The motivation of the current study is the numerical exploration of the effectiveness of acoustic excitation in controlling flow separation in an aeroengine representative compressor cascade without the endwalls. The cascade endwalls are intentionally removed to quantify the effect of acoustic excitation on profile loss behaviour of the cascade. Without the endwalls, this cascade is representative of high aspect ratio cascades in aeroengines. Therefore, the effectiveness of acoustic excitation in controlling flow separation can have a direct impact on the design of compressor cascades and blades. The investigations include the development of a computational modelling approach, a thorough exploration of the effects of acoustic excitation and comparison of external and internal acoustic excitations.

2. METHODOLOGY

In the methodology, details of the turbulence modelling approach IDDES are provided. Thereafter, the computational approach and acoustic excitation modelling in a computational environment are discussed.

2.1 Improved Delayed Detached Eddy Simulation (IDDES)

DES is a hybrid RANS/LES model that is superior to RANS in capturing separated flow characteristics and to LES in computational cost. The accuracy of DES model is sacrificed in B/L regions due to modelling approach in utilising RANS and blending between RANS and LES zones in separated flows. The boundary layer shielding approach in IDDES attempts to solve the blending between the two models employed. IDDES model is based on two-equation $k - \omega$ SST, with the following modifications to k and ω equations:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_j k)}{\partial x_j} = \tau_{ij} \frac{\partial u_i}{\partial x_j} + \frac{\partial}{\partial x_j} \left[(\mu + \sigma_k \mu_t) \frac{\partial k}{\partial x_j} \right] - C_\mu \rho \omega k l_{IDDES} \quad (1)$$

$$\begin{aligned} \frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho u_j \omega)}{\partial x_j} &= \frac{\gamma}{\nu_t} \tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta \rho \omega^2 + \frac{\partial}{\partial x_j} \left[(\mu + \sigma_\omega \mu_t) \frac{\partial \omega}{\partial x_j} \right] \\ &+ 2(1 - F_1) \frac{\rho \sigma_\omega}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} \end{aligned} \quad (2)$$

where ρ is density, k is turbulent kinetic energy (TKE), ω is specific dissipation, x_i represents spatial coordinates, t is time, μ is laminar viscosity, μ_t is turbulent eddy viscosity and l_{IDDES} is IDDES length scale given as;

$$\begin{aligned} l_{IDDES} &= \tilde{f}_d (1 + f_e) l_{RANS} + (1 - \tilde{f}_d) l_{LES} \\ l_{RANS} &= \frac{\sqrt{k}}{C_\mu} \\ l_{LES} &= C_{DES} \Delta \\ C_{DES} &= C_{DES1} F_1 + C_{DES2} (1 - F_1) \end{aligned} \quad (3)$$

where l_{IDDES} , l_{RANS} and l_{LES} are IDDES, RANS and LES length scales, respectively. $C_{DES1} = 0.78$ and $C_{DES2} = 0.61$ are model constants and F_1 is a blending function.

The LES length scale is given by:

$$\Delta = \min \{ C_\omega \max [d_\omega, h_{max}], h_{max} \} \quad (4)$$

where h_{max} is the cell maximum edge length and d_ω is the distance from the cell to the wall. $\tilde{f}_d$ in Eqn. 3 is an empirical blending function computed as:

$$\begin{aligned} \tilde{f}_d &= \max \{ (1 - f_{dt}), f_b \} \\ f_{dt} &= 1 - \tanh [(C_{dt1} \cdot r_{dt})^{C_{dt2}}] \\ r_{dt} &= \frac{\nu_t}{\kappa^2 d_\omega^2 \sqrt{0.5(S^2 \Omega^2)}} \\ f_b &= \min \{ 2 \exp(-9\alpha^2), 1.0 \} \\ \alpha &= 0.25 - d_\omega / h_{max} \end{aligned} \quad (5)$$

where κ is Karman constant, S is strain rate tensor magnitude and Ω is vorticity tensor magnitude. Further details can be found in Gritskevich [14] and Menter [15].

2.2 Computational Approach

For the numerical simulations, a NACA65-K48 linear compressor cascade is used, which is generated by 48° arc distribution over a NACA65 profile [16]. The operating conditions of the cascade at its aerodynamic design point (ADP) are provided in Table 1. The inlet Mach number is $Ma_1 = 0.67$ with a corresponding chord-based Reynolds number of $Re_c = 560 \times 10^3$. The flow turning angle across the cascade is $\Delta\beta = 42^\circ$. As the current study focuses on the LCC in the absence of the cascade endwalls, flow through the cascade does not experience flow separation at ADP. Therefore, an incidence angle of $i = 8^\circ$ is used as representative of off-design cascade operation.

TABLE 1: NACA65-K48 linear compressor cascade design parameters and operating conditions [16].

Inlet Mach Number	Ma_1	0.67	[-]
Inflow Angle	β_1	132	[$^\circ$]
Flow Turning	$\Delta\beta$	42	[$^\circ$]
Stagger Angle	β_s	112.5	[$^\circ$]
Chord Length	c	40	[mm]
Solidity	t/c	0.55	[-]

The computational domain is shown in Figure 1 along with the boundary conditions (BC). Two passages of the linear cascade are modelled with the use of periodic boundary conditions that account for the flow interactions between consecutive blades. The computational domain extends $0.8C_{ax}$ upstream of the cascade inlet whereas it extends $2.9C_{ax}$ downstream of the cascade exit following typical DES and turbomachinery best practice guidelines. For the boundary conditions, a total pressure inlet BC is used at the inlet boundary. At the downstream boundary, non-reflective pressure outlet BC is used. The reflection of sound waves may result in non-physical perturbations in the flow variables, which may result in an ambiguity on the effectiveness of acoustic excitation. Therefore, non-reflecting boundary condition (NRBC) is used to prevent the reflection of sound waves from the downstream boundary of the computational domain [17, 18]. In the pitchwise and spanwise boundaries, translational periodicity is used due to the symmetry in the LCC under consideration. Outlet static pressure is specified accordingly to satisfy the inlet Mach number, $Ma_1 = 0.67$. For the blade surfaces, no-slip adiabatic wall boundary conditions are applied.

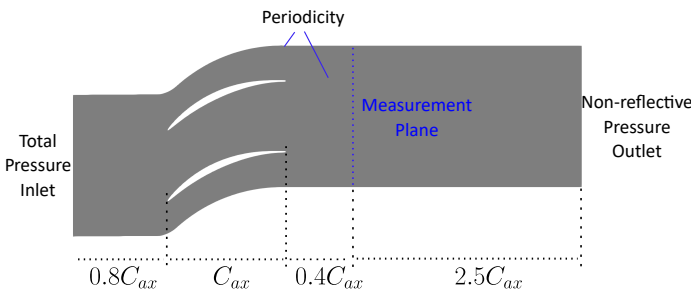


FIGURE 1: Computational domain and boundary conditions.

A hexahedral O-C-H grid topology is used for computational grid generation as shown in Figure 2. Grid sizing is determined based on a grid convergence study that revealed a grid size $\Delta < \delta/20$ in the separated flow regions, where δ is the boundary layer thickness. Numerical computations are carried out in ANSYS-Fluent, which is a cell-centred finite volume flow solver. A fully implicit pressure-based solver is utilized. Second-order upwind spatial discretization is used for the convective terms while Green-Gauss Node-Based spatial discretization is used for gradients and derivatives. Total variation diminishing (TVD) scheme is used for flux limiting in the numerical solver. Second-order implicit Newtonian dual-time stepping method is used for transient formulations with 15 pseudo sub-iterations per time advancement for solution of mean flow and turbulent quantities. Steady $k-\omega$ SST based RANS computations are used as precursor simulations to transient $k-\omega$ SST IDDES model.

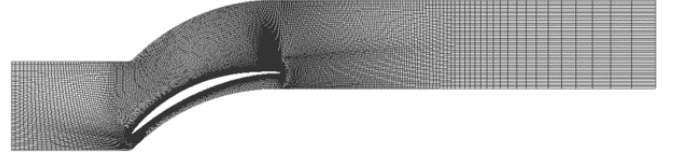


FIGURE 2: Computational grid around a single LCC passage.

2.3 Acoustic Excitation Modelling

In this study, monochromatic planar sound waves are used for the investigation of acoustic excitation effectiveness in controlling flow separation. The sound waves are generated by the use of transient boundary conditions for both external and internal acoustic excitation as given in Equation 6 for the time dependent total pressure and total temperature profiles.

$$\begin{aligned} P_t &= P_{t,\infty} \left(1 + A_m e^{i(kx_i - \omega t)} \right) \\ T_t &= T_{t,\infty} \left(1 + A_m \frac{\gamma - 1}{\gamma} e^{i(kx_i - \omega t)} \right) \end{aligned} \quad (6)$$

where $P_{t,\infty}$ and $T_{t,\infty}$ are the inlet total pressure and temperature, respectively, in the absence of sound waves, A_m is excitation amplitude in percentage of $P_{t,\infty}$, $k = \sqrt{k_x^2 + k_y^2 + k_z^2} = \omega/c_0$ the wave number of planar waves and $\omega = 2\pi f_{exc}$ the circular frequency, f_{exc} excitation frequency and c_0 the speed of sound, as demonstrated in Figure 3.

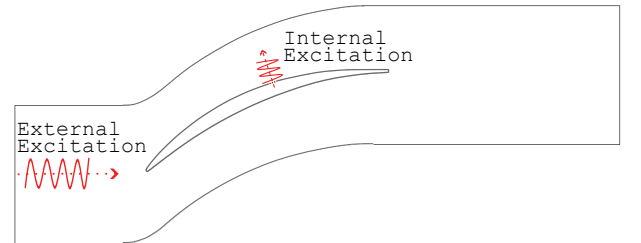


FIGURE 3: Implementation of external and internal acoustic excitation.

In external acoustic excitation, a distributed sound source is modelled at the inlet boundary of the computational domain. In internal acoustic excitation, on the other hand, sound waves are introduced from a thin slot (i.e., $d/C = 0.02$, where d is the excitation slot width) located on the blade suction surface. The sound wave frequencies for acoustic excitation of the flow through the LCC are determined from the uncontrolled flow frequency spectra. Accordingly, transient data is collected at the monitor locations P1-P3 as shown in Figure 4, where P1 is located at the origin of separation while the rest of the monitor points are located at the centre line of the separated shear layer. Therefore, the data collected at these points reflects the unsteady characteristics of the separated shear layer and vortex shedding downstream.

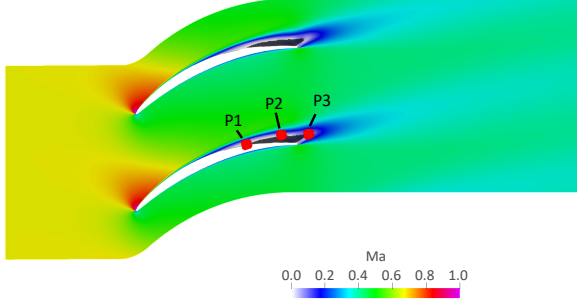


FIGURE 4: Monitor locations within the separated shear layer.

The spectral characteristics at each monitor location are shown in Figure 5 for the uncontrolled flow. The modal frequencies in the separated flow are $St_c = 0.187$, 0.409 , and 0.618 in terms of Strouhal number, whilst $St_c = 0.618$ being the most dominant frequency. Therefore, the acoustic excitation is implemented with these three modal frequencies for both external and internal acoustic excitation.

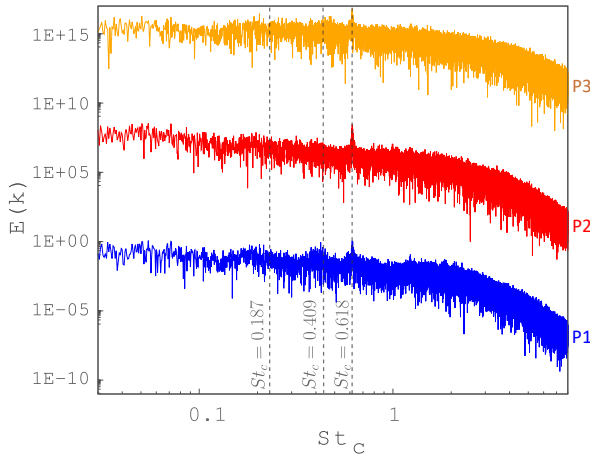


FIGURE 5: Streamwise evolution of turbulent kinetic energy spectra for the uncontrolled flow. The amplitude of each successive spectrum is increased by four orders of magnitude for clarity.

3. RESULTS

The investigations are carried out for both external and internal acoustic excitation. Three excitation frequencies are used

at a constant excitation amplitude for both external and internal acoustic excitation. These excitation frequencies correspond to the modal frequencies in the uncontrolled flow turbulent kinetic energy spectrum. An excitation slot is used for the internal acoustic excitation, which is located at the onset of flow separation over the blade suction surface. A distributed sound source is used on the inlet boundary of the domain for external acoustic excitation. Thereafter, an additional range of excitation amplitudes is investigated for internal excitation.

The discussion is divided into two main subsections. First, the effect of acoustic excitation frequency on the flow field, the physical mechanism behind the interactions of sound waves and flow separation and the overall change in the cascade performance is investigated for both external and internal excitation. Secondly, the effect of sound amplitude is explored.

3.1 The Effect of Excitation Frequency

3.1.1 Flow Field Analyses. The effect of acoustic excitation frequency on the cascade flow field is analysed in this section. The modal frequencies in the uncontrolled flow in Figure 5 are used at a constant excitation amplitude $SPL = 151dB$, which was obtained to be the most effective excitation amplitude for the LCC with endwalls in our earlier research [1]. The effects of external and internal acoustic excitations on the flow through the cascade are shown in Figure 6 for the streamlines superposed on the normalised mean velocity contours. In the uncontrolled case, the flow over the suction surface of the LCC blade separates at $x/c \approx 0.6$ for the conditions under investigation.

External acoustic excitation of the flow through the LCC without the endwalls has little to no effect on reducing or suppressing the flow separation over the blade suction surface for all three of the excitation frequencies under consideration. For internal excitation, on the other hand, the extent of flow separation is considerably reduced. The volume of separated flow over the suction surface reduces by $\sim 48\%$ compared to the uncontrolled flow. However, no flow reattachment is observed. Furthermore, no superiority in the excitation frequencies is observed for internal acoustic excitation.

The results are compared in terms of RSS ($-\rho\overline{u'v'}$) distribution as it is a measure of turbulence mixing. In wall-bounded flows, turbulent mixing results in momentum transfer to the near-wall regions and energises the low-momentum flow in these regions. Therefore, the differences in the effectiveness of internal and external acoustic excitations in controlling the flow separation through the LCC are investigated by comparison of the spanwise RSS contours in Figure 7. The results indicate no considerable change in the RSS distribution through the cascade for external acoustic excitation. When the flow is internally excited by sound waves, a substantial increase in the RSS over the blade suction surface is observed. The results indicate a significant upstream movement of the location where RSS is generated over the LCC blades, while the magnitude of RSS increases across the shear layer. This rise in the RSS over the LCC implies improved turbulent mixing, which enhances momentum transfer across the separated shear layer, energising the separated flow regions to become more resistant to flow separation. The results also indicate no major difference between different excitation frequencies.

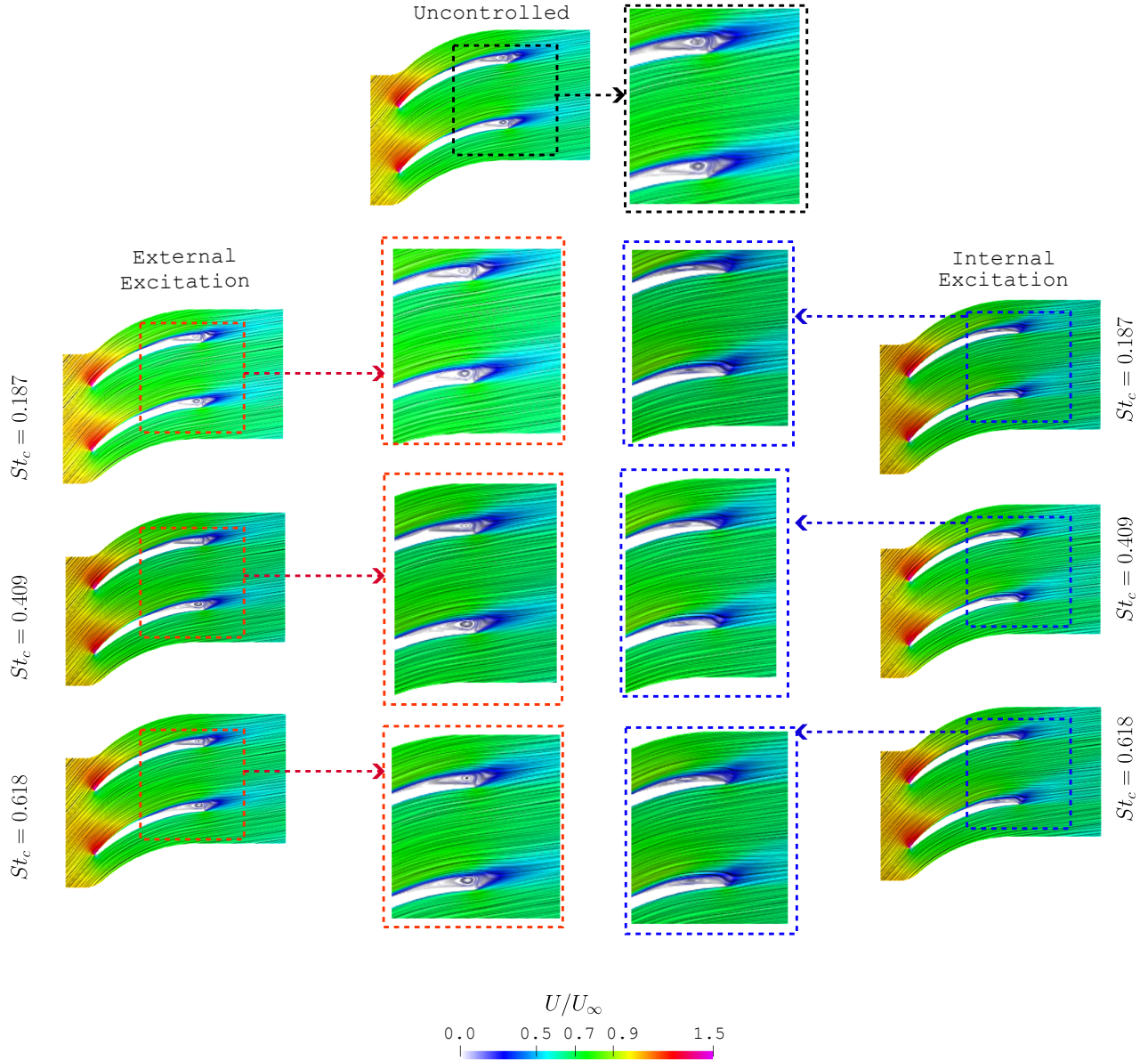


FIGURE 6: The effect of acoustic excitation on the flow field of LCC without endwalls.

3.1.2 Physical Mechanism for the Effectiveness of Acoustic Excitation. Further investigations are carried out for a better understanding of the physical phenomenon behind the effectiveness of internal acoustic excitation, while external excitation has no major effect on the cascade flow. The comparison of normalised spanwise vorticity contours is shown in Figure 8 for uncontrolled flow, flow excited by external acoustic waves, and flow excited by internal sound waves.

In the uncontrolled flow, separated flow over the blade suction surfaces of the LCC blades at $x/c \approx 0.6$ generates a shear layer that rolls up and eventually breaks down to vortical structures at $x/c \approx 0.8$. The centre of the separated shear layer is located away from the blade suction, and a separated flow region is generated between the blade suction surface and the shear layer.

For the cascade flow excited by external sound waves, the

streamwise evolution of the separated shear layer is remarkably different for all three excitation frequencies under investigation. The excitation frequency $St_c = 0.187$ results in an earlier roll-up and breakdown of the separated shear layer over the cascade, while the excitation frequency $St_c = 0.409$ has no major effect on the shear layer development. The third excitation frequency, $St_c = 0.618$ results in the generation of smaller-scale and coherent vortical structures. However, the shear layer and hence the coherent vortices are located away from the separated flow region, resulting in no major momentum transfer across the shear layer.

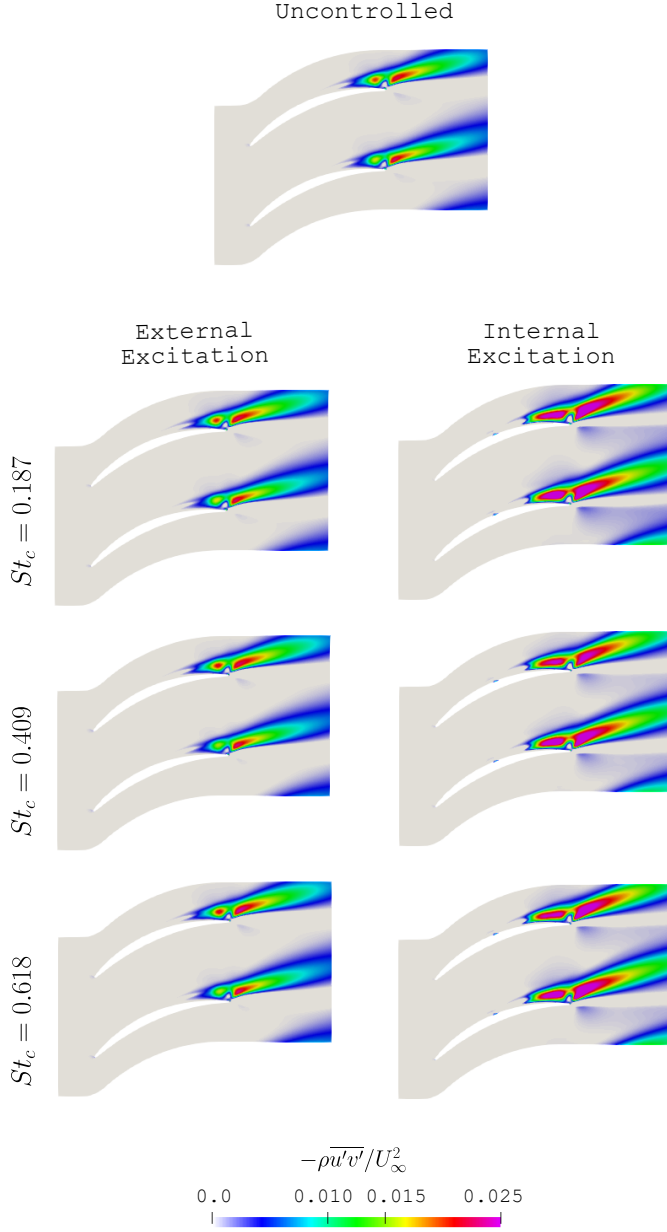


FIGURE 7: The effect of acoustic excitation on spanwise Reynolds Shear Stress distribution.

A considerably greater upstream roll-up and breakdown of the separated shear layer is observed in internally excited flow compared to uncontrolled and externally excited flows. Earlier breakdown of the shear layer enhances momentum transfer across the shear layer in internally excited flow because of two reasons: first, the shear layer is sufficiently close to the blade suction surface; second, more coherent vortices are generated that are more energetic, and hence, improve the energy transfer to the separated flow regions.

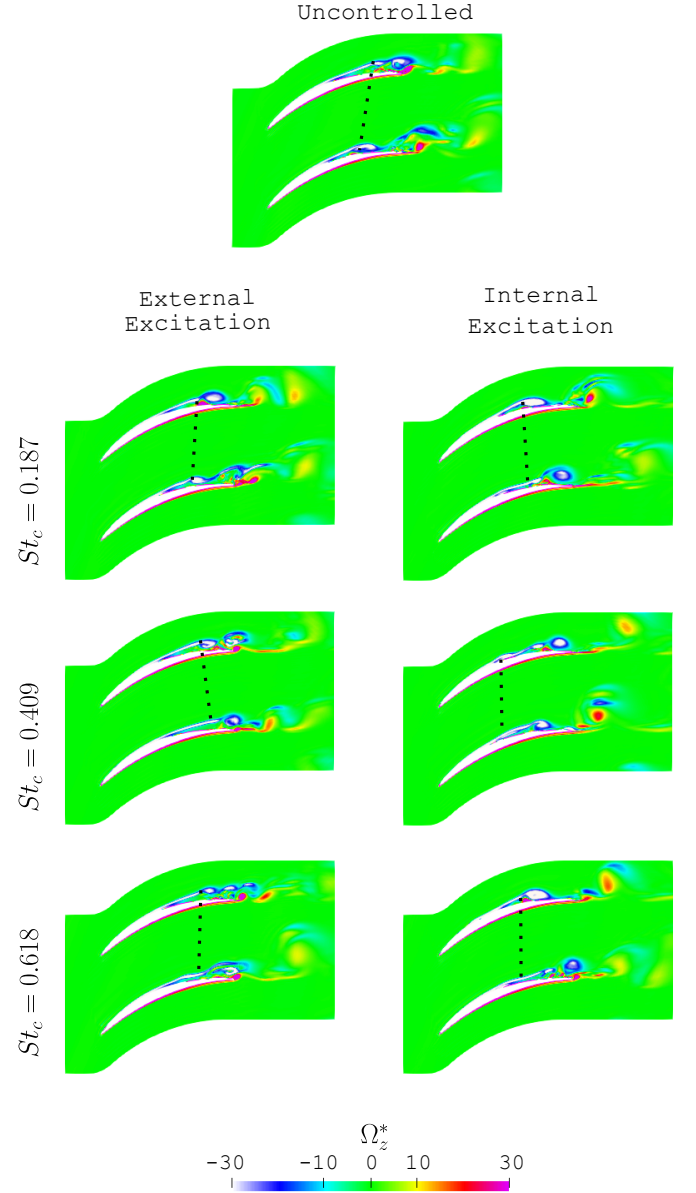


FIGURE 8: Normalised spanwise vorticity Ω_z^* contours.

These changes in the shear layer evolution and vortex shedding characteristics are illustrated in Figure 9 by iso-surfaces of the Q-criterion. The results indicate an earlier breakdown of the separated shear layer and the generation of coherent vortical structures when the flow is excited by internal sound waves. These vortices are located in the vicinity of the blade suction surface and energises the near-wall low-momentum flow. Although a change in the coherence of vortices is observed with varying excitation frequency, vortex shedding takes place in the vicinity of the suction surface in all cases that results in strong interactions with the near-wall flow. External acoustic excitation, unlike internally excited flow, is unable to generate coherent vortices for the majority of the suction surface.

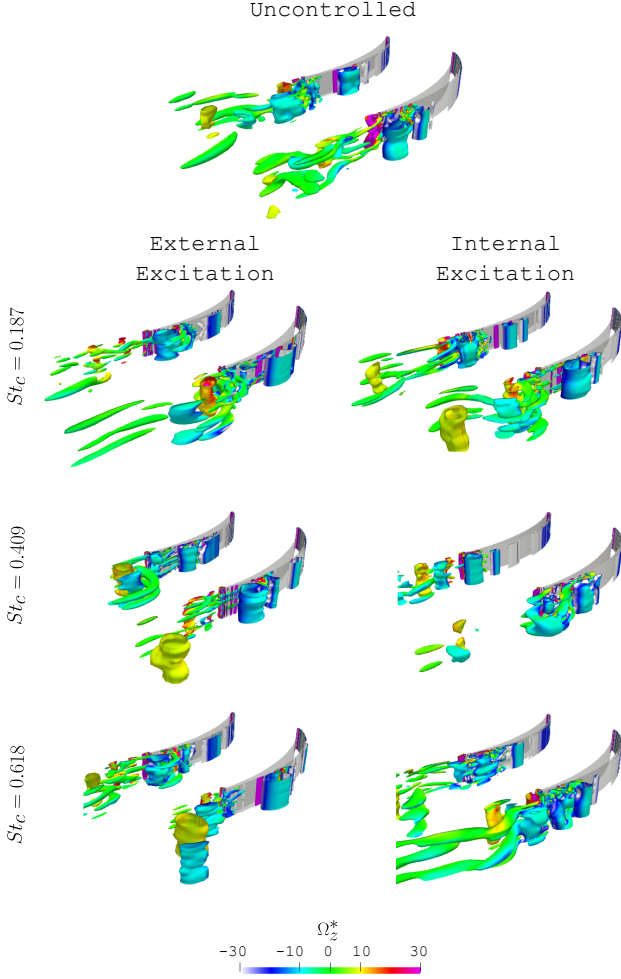


FIGURE 9: Iso-surfaces of Q -criterion at $Q = 1 \times 10^9$ coloured by Ω_z^* .

The comparison of the turbulent kinetic energy (TKE) spectra at the monitor locations shown in Figure 4 are illustrated in Figure 10. The results indicate that external acoustic excitation has no major effect in the TKE spectra under the sound wave frequencies considered. Internal acoustic excitation, on the other hand, results in generation of harmonic frequencies, which implies generation of smaller turbulent structures at higher frequencies. Furthermore, unlike external excitation, there is a significant energy transfer from lower frequency, higher scale structures to higher frequency and lower scale turbulent structures in internal acoustic excitation. Therefore, these findings suggest that internal acoustic excitation results in an earlier transition in the separated shear layer and enhances the energy transfer across the shear layer into the near-wall separated flow regions.

3.1.3 Excitation Effect on the Cascade Performance.

The overall effect of acoustic excitation is quantified by the use of the spanwise distribution of the pitch- and mass-averaged total pressure loss coefficient, ζ_t , as given in Equation 7. The corresponding total pressure loss coefficients for external and internal acoustic excitation are compared to uncontrolled flow as illustrated in Figure 11. The results are compared at the measurement

plane of the cascade at $x/c = 0.4$ downstream of the blade trailing edge. External acoustic excitation of the flow results in no considerable change in the cascade performance for any of the excitation frequencies investigated. This is in agreement with flow field analyses in previous sections.

$$\zeta(y, z) = \frac{P_{01} - P_0(y, z)}{P_{01} - P_1} \quad (7)$$

$$\zeta_t = \iint_{MP} \zeta(y, z) dy$$

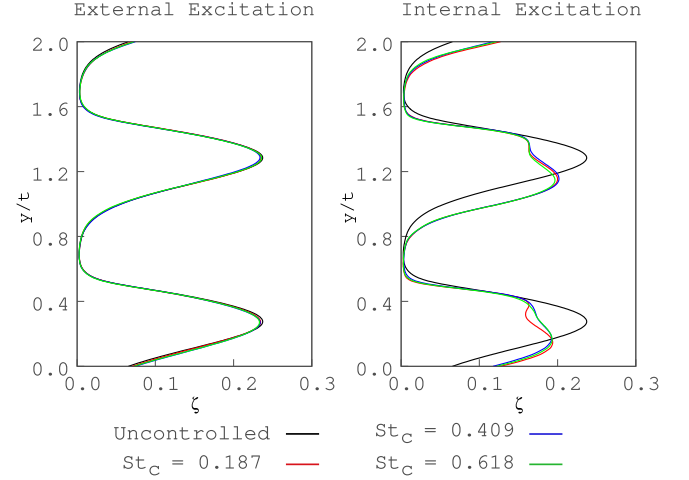


FIGURE 11: Pitchwise total pressure loss coefficient profiles at the measurement plane for external and internal excitation frequencies.

Internal acoustic excitation of the cascade flow results in a reduction in the maximum total pressure loss coefficient at the cascade measurement plane by $\Delta\zeta_{max} \approx 16\%$, as demonstrated in Figure 12. A weak dependency, $\Delta\zeta_{max} \leq 1\%$, on the excitation frequency is observed. The results indicate a pitchwise wider loss profile, while the peak total pressure loss coefficient is reduced, which is more favourable for cascade design.

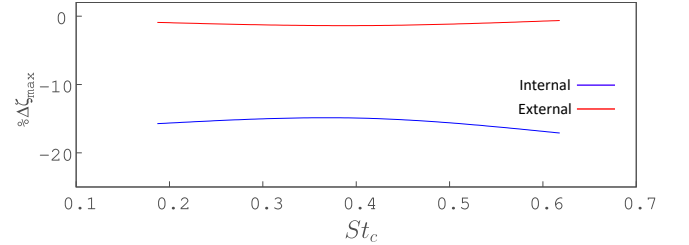


FIGURE 12: The change in the peak value of the total pressure loss coefficient with internal and external acoustic excitation.

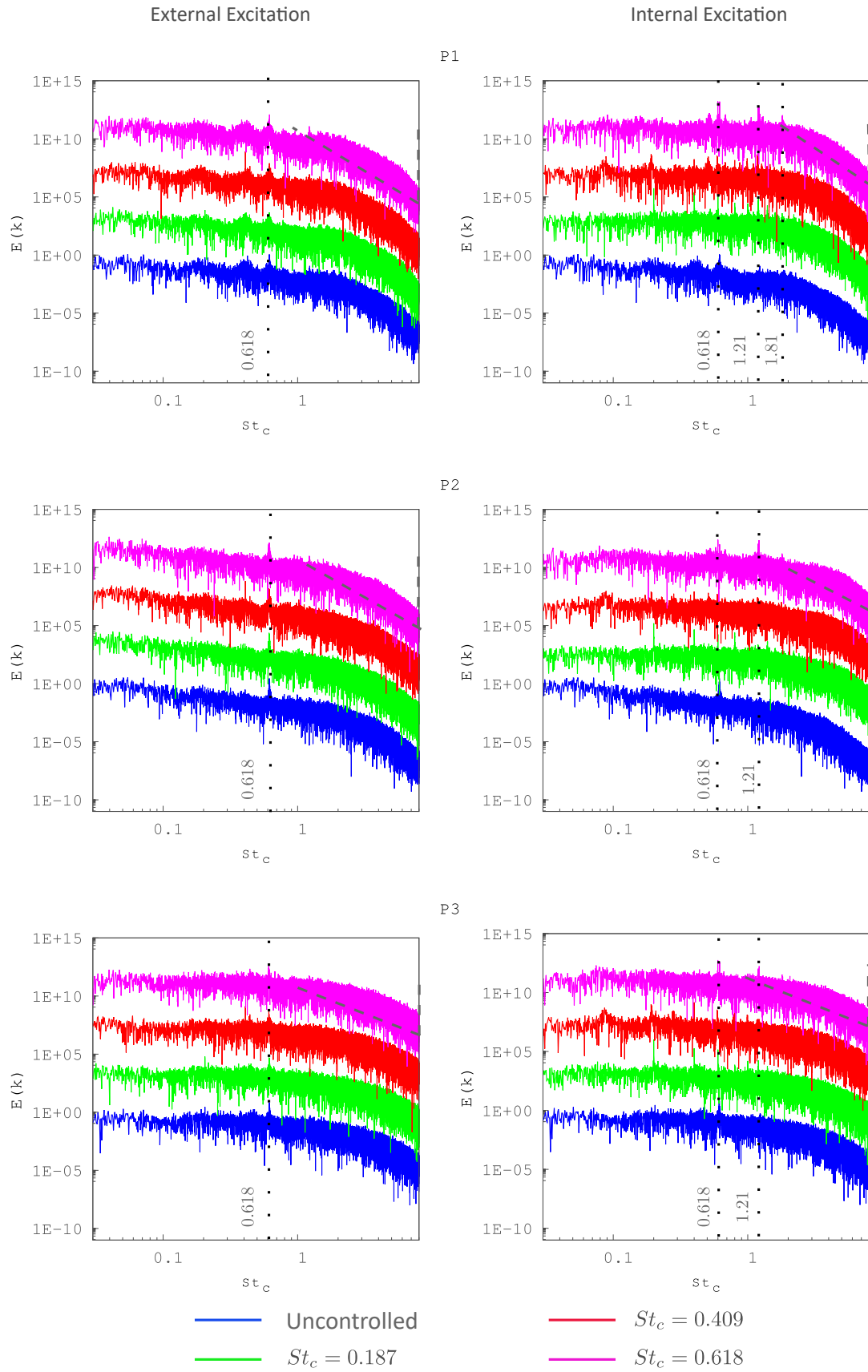


FIGURE 10: Streamwise evolution of turbulent kinetic energy spectra with external and internal acoustic excitation. The amplitude of each successive spectrum is increased by four orders of magnitude for clarity.

3.2 The Effect of Excitation Amplitude

Investigation of the effect of excitation frequency in the previous section indicated that external acoustic excitation has negligible effect in controlling flow separation in the cascade. Therefore, the effect of sound amplitude is explored in this section for internal acoustic excitation only. The range of sound wave amplitude in $125\text{dB} \leq A_m \leq 151\text{dB}$ is explored. The initial excitation amplitude $A_m = 151\text{dB}$ is based on our earlier findings in [1]. In this section, the excitation amplitude A_m in Equation 6 is consistently halved from $A_m = 0.01P_{t,\infty}$ to $A_m = 0.0005P_{t,\infty}$ at the excitation frequency $St_c = 0.618$.

3.2.1 Flow Field Analyses. The effect of sound wave amplitude on the effectiveness of acoustic excitation in controlling flow separation is investigated by comparison of the flow field in Figure 13. The flow field around the cascade coloured by the normalised velocity magnitude shows a reduction on the extent of the flow separation over the blade suction surfaces with a resultant narrower wake downstream of the cascade. Although acoustic excitation has a significant effect in reducing the flow separation in the LCC, the results indicate no profound effect of sound wave amplitude on the effectiveness of acoustic excitation. This finding is attributed to the fact that the sound source is located at the onset of flow separation on the blade suction surface and, hence, affecting the evolution of the shear layer from the initial phases and onwards. Therefore, even the smallest sound wave amplitude considered in this study provides similar flow control authority to the higher sound wave amplitudes. These findings are in agreement with earlier findings in the literature for internal acoustic excitation of low speed flows.

3.2.2 The Effect of Excitation Amplitude on Cascade Performance. The effect of acoustic excitation amplitude on the cascade performance is compared in Figure 14 in terms of the pitchwise distribution of total pressure loss coefficient at the measurement plane. The results indicate that the sound amplitude has no major effect on the effectiveness of internal acoustic excitation that the overall impact of acoustic excitation on the cascade performance remains unaffected with increasing sound amplitude. The overall effect of acoustic excitation amplitude is that there is a $\Delta\zeta_{max} \approx 16\%$ reduction in the total pressure loss coefficient for the range of sound amplitudes explored. Therefore, the results indicate that internal acoustic excitation can provide a significant improvement on the cascade performance even at relatively low excitation amplitudes, i.e., $A_m = 125\text{dB}$. The investigation for even smaller sound amplitudes remains as a future work.

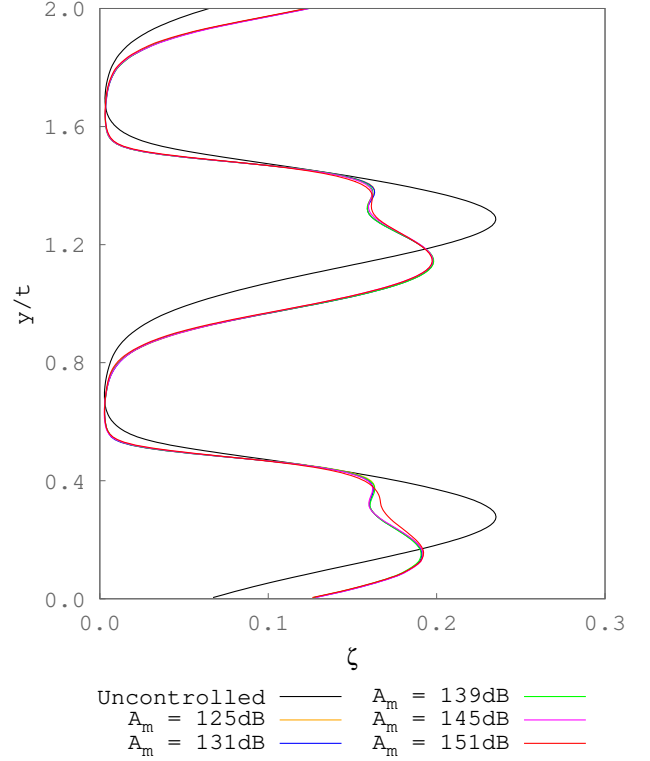


FIGURE 14: The effect of acoustic excitation amplitude on pitchwise total pressure loss coefficient distribution at MP.

4. CONCLUSIONS

This study investigates the effectiveness of external and internal acoustic excitation in controlling flow separation in a linear compressor cascade numerically. A NACA65-K48 LCC is used for the investigations that operates at $Ma = 0.67$ and $Re_c = 560 \times 10^3$ at an incidence angle of $i = 8^\circ$, which is representative of an aeroengine.

It has been observed that external acoustic excitation has little to no effect in improving the separation characteristics in the linear compressor cascade under investigation. Excitation with the modal frequencies has no effect in transition of the separated shear layer, and hence, the improvement of energy transfer across the shear layer remains negligible. On the other hand, internal acoustic excitation of the flow from an excitation slot located on the blade suction surface at the onset of separation results in an earlier transition in the separated shear layer and generation of harmonic frequencies at the turbulent kinetic energy spectra, which improves the energy transfer across the shear layer. Therefore, results indicate that internal acoustic excitation of the separated flow improves the separation characteristics by triggering an earlier transition in the separated shear layer and changing the vortex roll-up and shedding characteristics. Further investigation of the impact of sound amplitude on the effectiveness of internal acoustic excitation indicated that sound amplitude has negligible effect on the effectiveness of acoustic excitation for the range of amplitudes considered in $125\text{dB} \leq A_m \leq 151\text{dB}$.

It has been shown that internal acoustic excitation can significantly improve the flow separation characteristics in a linear compressor cascade without the cascade endwalls operating at

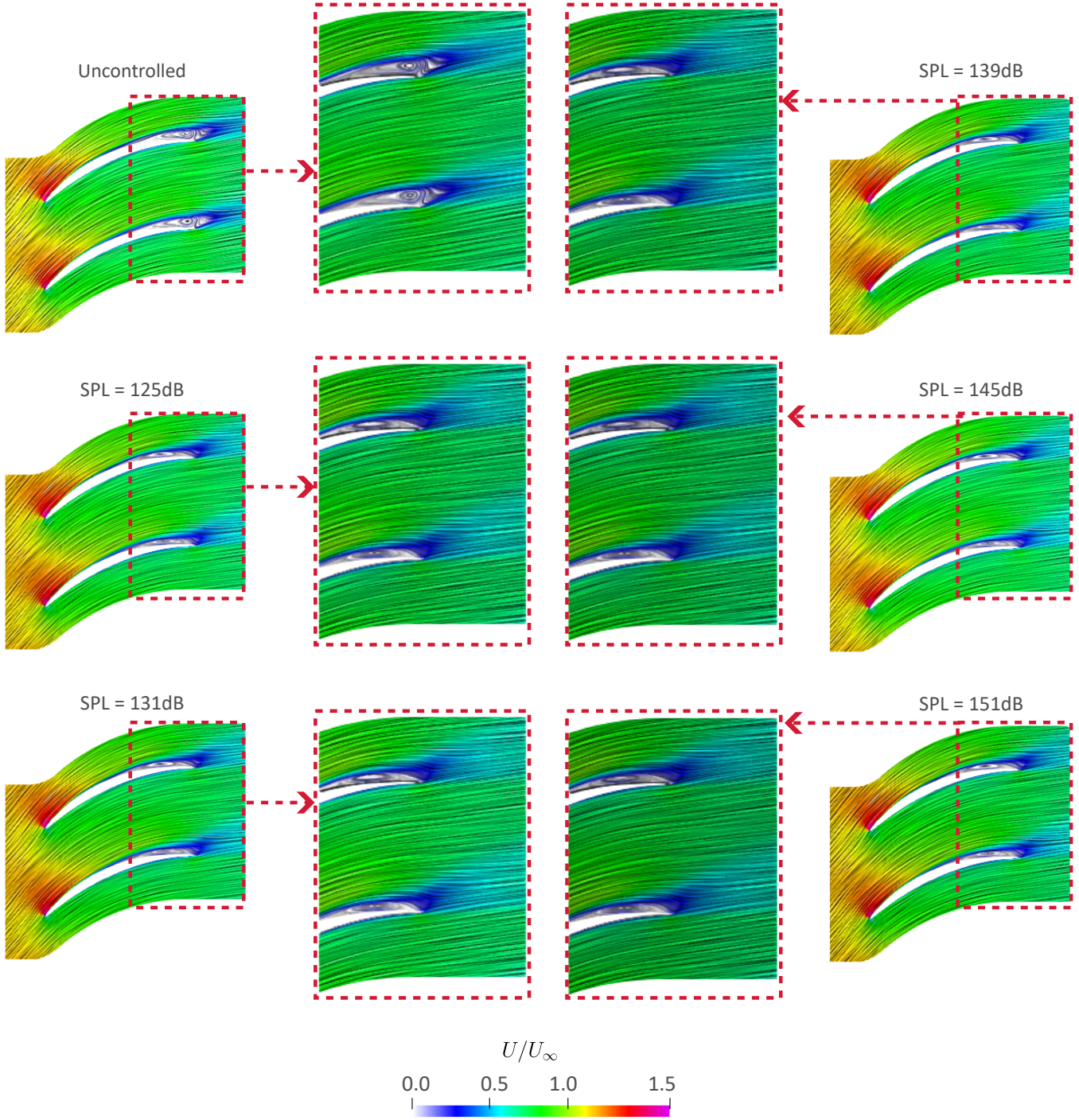


FIGURE 13: The effect of acoustic excitation on the flow field of LCC without endwalls.

high-speeds. In this form, the linear compressor cascade under investigation is representative of a high aspect ratio cascade in an aeroengine. Therefore, it is anticipated that the findings of study can serve as a means of flow control in high-speed compressor cascades. Further investigations on the effective excitation amplitudes and locations remain as a future work.

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