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Improved Delayed Detached Eddy Simulations Applied to a NACA0015 Aerofoil Subject to Acoustic Excitation

Seyfettin Coskun*, Vassilios Pachidis† and Iroizan Ubulom ‡
Cranfield University, Bedfordshire, MK43 0AL, UK

Marko Bacic§
Rolls-Royce plc., Derby, DE21 8BJ, UK

The effect of acoustic excitation on the aerodynamic performance of NACA0015 aerofoil at $\alpha = 11^\circ$ and $Re_c = 1.0\ x10^6$ based on $c = 0.35m$ chord length is investigated numerically using Improved Delayed Detached Eddy Simulations (IDDES). Flow separation is observed over the suction surface in the uncontrolled flow that forms a separated shear layer, resulting in aerodynamic performance degradation. External acoustic excitation is used in controlling the flow separation by exciting the separated shear layer. Acoustic excitation frequency and amplitude are the control parameters considered. The flow field is excited at a frequency of the most amplified disturbances and at first harmonic and sub-harmonic frequencies with a constant excitation amplitude. Unlike the harmonics, when the separated shear layer is excited at $F+ = 1$, the separation characteristics of the uncontrolled flow field are significantly altered. Unsteady disturbances are locked into the excitation frequency and transition is promoted within the shear layer. A separation bubble is generated over the suction surface with a reattachment region aft of the aerofoil surface. Vortex coherence and organized wake structures are also improved. The effect of excitation amplitude is investigated at the frequency of the most amplified disturbances. Increasing the excitation amplitude has two predominant impacts; it delays the boundary layer separation and advances the reattachment location, thereby reducing the separation bubble length. The results also suggest that there is a maximum effective acoustic excitation amplitude.

I. Nomenclature

f_0	=	fundamental frequency of the most amplified disturbances within the shear layer
f_{exc}	=	acoustic excitation frequency
A_m	=	acoustic excitation amplitude, in percentage of U_∞
C_p	=	pressure coefficient
C_l, C_d	=	aerofoil lift and drag coefficients
C_f	=	skin friction coefficient
c	=	chord length
U_∞	=	freestream velocity magnitude
$\overline{U}$	=	mean streamwise velocity magnitude
ν	=	kinematic viscosity of air
α	=	angle of attack
Re_c	=	Reynolds number based on chord length, $U_\infty c/\nu$
$F+$	=	reduced frequency, f_{exc}/f_0
Δt	=	numerical time step
τ	=	$t(U_\infty/c)$, convective time
URANS	=	Unsteady Reynolds-averaged Navier-Stokes
IDDES	=	Improved Delayed Detached-Eddy Simulation

*PhD. Researcher, Propulsion Engineering Centre, School of Aerospace Transport and Manufacturing, seyfettin.coskun@cranfield.ac.uk.
†Professor, Propulsion Engineering Centre, School of Aerospace Transport and Manufacturing, v.pachidis@cranfield.ac.uk.
‡PhD., Propulsion Engineering Centre, School of Aerospace Transport and Manufacturing, Iroizan.A.Ubulom@cranfield.ac.uk.
§PhD., Rollsy-Royce plc.

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II. Introduction

Flow separation over aerodynamic surfaces such as an aircraft wing or a turbomachinery blade surface is often encountered that results in aerodynamic performance degradation. These performance losses are relatively more pronounced at near-stall operations and any reduction in flow separation can provide considerable performance improvements. Therefore, control of flow separation to improve unsteady flow characteristics and aerodynamic performance has been one of the main subjects of fluid dynamics research for many years [1, 2].

Acoustic excitation is a flow control technique that takes advantage of the instabilities present in a separated flow field to suppress the flow separation and improve the aerodynamic performance. It has been demonstrated by several studies that acoustic excitation can suppress flow separation and improve aerodynamic performance specifically for low-Reynolds number laminar flows when applied at an effective excitation frequency and amplitude[3–9]. Zaman and McKinzie [4] and Hsiao et al. [10] observed that acoustic excitation is most effective at near-stall angle-of-attacks when applied at the frequency of the most amplified disturbances of the shear layer. The instability frequency of the shear layer is locked into the excitation frequency of sound waves such that transition to turbulence in the seprated shear layer is promoted, resulting in advancement of reattachment location, shifting of separation location downstream and hence a reduced separation length as reported by [7, 11]. Acoustic excitation amplitude, on the other hand, has a more intricate effect on aerofoil performance. An increase in excitation amplitude is accompanied by an increase in lift and reduction in drag when applied above a minimum effective amplitude threshold as the rapid transition to turbulence is promoted with increasing excitation amplitude, which is more resistant to flow separation. Moreover, there is a maximum excitation amplitude beyond which the effect of amplitude increment does not contribute to lift any further [12].

Acoustic excitation can be applied in the form of both internal and external excitation, depending on the location of sound source. In external acoustic excitation, a sound source is located away from the geometry of interest whereas sound source is located inside the boundary layer, usually on or underneath a surface of geometry in internal excitation. Although smaller excitation amplitudes are required for internal acoustic excitation due to being closer to the separated flow and hence being diffused less, the efficiency of the method is affected by the excitation location and orientation of sound source [13]. Since optimum application parameters for internal excitation are not clear to the date yet, external acoustic excitation is implemented in the current work, acoustic excitation frequency and amplitude being the parameters of interest.

Highly unsteady behaviour of near-stall angle-of-attack flow regimes requires use of scale resolving turbulence models such as Large Eddy Simulation(LES) for accurate simulation of a variety of length scales present in the flow field with resolution of acoustic waves and sound-flow interactions. However, the computational cost of an LES is prohibitive for relatively high Reynolds number flows and hybrid methods which combine advantages of both RANS and LES methods, can be suited to such flows. Detached-Eddy Simulation (DES) is one of the hybrid RANS-LES methods that takes advantage of the RANS modelling in near-wall regions and LES elsewhere with a lower computational requirement [14] compared to a classical LES. Improved Delayed Detached-Eddy Simulation (IDDES) is an improved version of DES resolving log-layer mismatch, as well as modelled stress depletion encountered in a classical DES [15]. Therefore, it is anticipated that IDDES provides required accuracy with a relatively reasonable computational cost for the purposes of the current work.

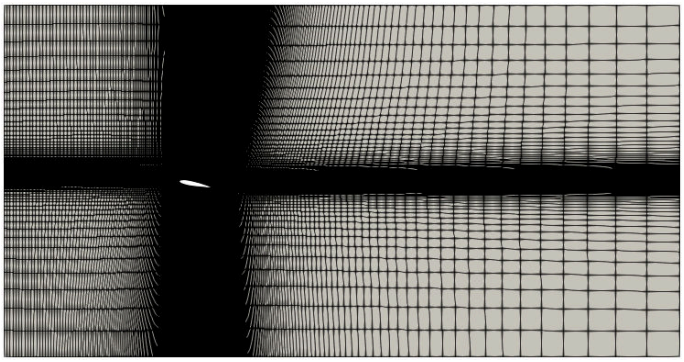
The aim of this paper is the numerical investigation of acoustic excitation effects on a flow over NACA0015 at near-stall angle-of-attack operating at 1 million of Reynolds number with a computational approach with IDDES. Almost entire research conducted on flow control through acoustic excitation in open literature focuses on low-Reynolds number applications for control of laminar flow separation. In the current work, relatively high Reynolds number applications of acoustic excitation have been conducted computationally. The investigations include IDDES method validation for the problem of interest and a parametric study on the effects of excitation frequency and amplitude for optimization of excitation parameters.

III. Computational Setup and Methodology

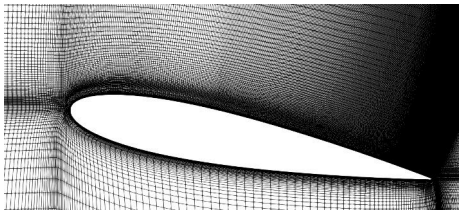
A NACA0015 aerofoil with $c = 0.35m$ and $Re_c = 1$ million based on chord length operating at $\alpha = 11^\circ$ is used as the baseline model. Near-stall separation characteristics are investigated in detail in the experimental work reported in [16]. Numerical computations are based on ANSYS-Fluent, which is a cell-centred finite volume flow solver. A fully implicit pressure-based solve is utilized. Second-order numerical spatial discretization is used for the pressure, momentum and energy while Green-Gauss Node-Based spatial discretization is used for gradients and derivatives. 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. $k - \omega$ SST based RANS computations are used as

precursor to transient $k-\omega$ SST IDDES model.

A computational domain with a size of $L_C\ xL_N\ xL_Z = 20c\ x10c\ x\ 0.2c$ is used as shown in Fig. 1. A computational time step independence study revealed that a time step $\Delta t = 2.5x10^{-2}csin(\alpha)/U_\infty$ provides temporal resolution independent solutions.



(a) Spanwise view



(b) Near wall refinement

Fig. 1 Computational domain.

IV. Results

All the results are obtained at $Re_c = 1.0\ x10^6$ based on chord length and at $\alpha = 11°$. The uncontrolled flow is analysed by a $k-\omega$ SST based IDDES model which is a hybrid RANS/LES method. Sound waves are introduced into the flow field by utilizing unsteady inlet velocity boundary conditions in the form of sine waves as given in Eqn. 1:

$$U_{inlet} = U_\infty(1 + A_m sin(2\pi f_{exc} t)) \tag{1}$$

A schematic of the acoustic waves implementation into the computational domain is shown in Fig. 2. The acoustic waves are generated by the unsteady inlet velocity boundary condition with a required wave amplitude and frequency. Downstream travelling waves interact with the separated shear layer over the aerofoil suction surface. In the downstream boundary of the computational domain, non-reflective outlet boundary condition is used to prevent any reflection of sound waves back into the computational domain.

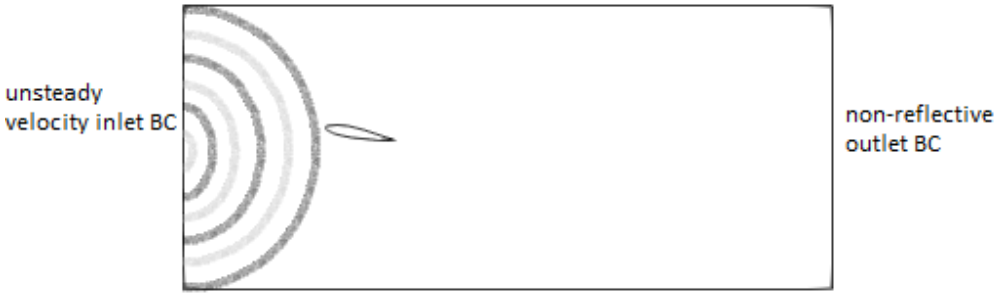


Fig. 2 Schematic of acoustic waves implementation into the computational domain.

Acoustic excitation frequency, f_{exc}, and amplitude, A_m, in Eqn. 1 are the main parameters investigated in the present work. The flow field is excited with the natural frequency of the disturbances present in the uncontrolled flow separated shear layer as well as the first sub-harmonic and harmonic of the natural frequency. The excitation amplitude is varied from $A_m = 1\%$ to $A_m = 10\%$.

A. Unexcited Flow

The numerical study of highly unsteady and non-linear characteristics of separated flows requires sophisticated computational models that are capable of resolving the turbulent scales present in the flow field such as Large Eddy Simulation (LES) or Direct Numerical Simulation (DNS). However, the computational costs of such methods are prohibitive, especially when applied to high Reynolds number flow cases. The widely used Reynolds Averaged Navier-Stokes (RANS), on the other hand, are not capable of capturing the unsteady characteristics of separated flows sufficiently. Hybrid RANS/LES methods are alternative methods to scale resolving methods that provide improved accuracy compared to URANS models. Detached Eddy Simulation (DES) is one of such methods that combines URANS and LES methods, such that URANS models are utilized within the boundary layer and LES elsewhere. Improved Delayed Detached Eddy Simulation is a variant of DES that eliminates earlier problems in DES such as log-layer mismatch. IDDES is used in the present work due to its promising capabilities in separated flows.

Time and span averaged C_p and C_f distributions on aerofoil surfaces are used as computational model validation metrics, as shown in Fig. 3. The C_p distribution over the aerofoil compares reasonably well with experimental data provided by Siauw [16]. The numerical prediction of the C_f distribution predicts the separation location at $x/c = 0.6$ whereas it is found at $x/c = 0.7$ in the experimental work as reported in [16]. This study therefore concludes that IDDES provides sufficient accuracy for further investigations on the control of separated flow by acoustic excitation.

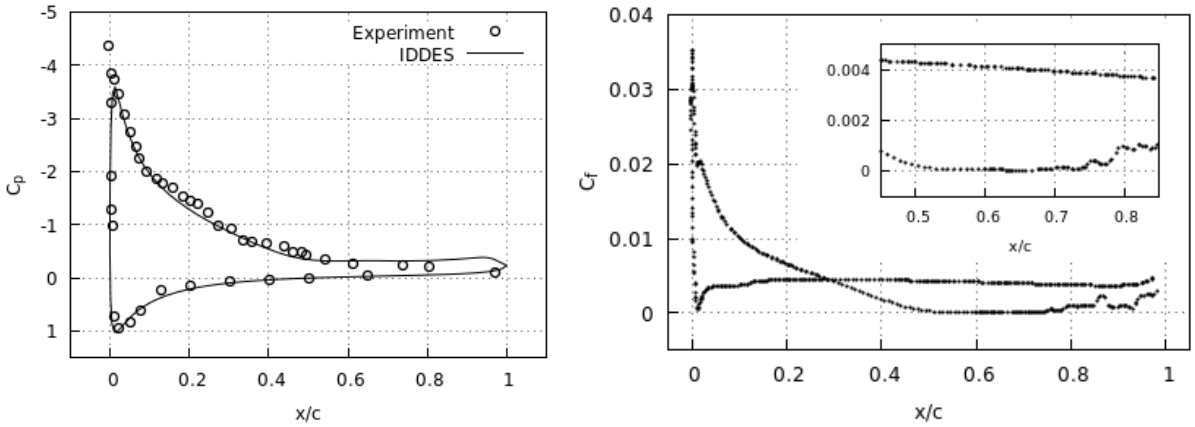


Fig. 3 Time and span averaged C_p and C_f distributions.

B. Effect of Excitation Frequency

One of the main parameters on the effectiveness of acoustic excitation of a separated flow is the excitation frequency. According to the findings of Zaman and McKinzie [4] and Hsiao et al. [10], acoustic excitation is most effective when applied with the frequency of the most amplified disturbances in the uncontrolled flow shear layer for near-stall angle-of-attacks. Therefore, the effect of excitation frequency on the baseline flow field is considered in this section. Acoustic excitation is applied on the baseline flow field at three different non-dimensional excitation frequencies, at $F+ = 0.5$, 1.0 and 2.0, where $F+ = f_{exc}/f_0$, which are the first sub-harmonic, natural frequency of unsteady disturbances present in the baseline flow shear layer and the first harmonic of the natural frequency, respectively. The excitation amplitude is kept constant at $A_m = 1.8\%\ U_\infty$ whilst the excitation frequency is altered. The effectiveness of acoustic excitation is considered in terms of time- and span-averaged C_p and C_f distributions as shown in Fig. 4 as well as aerodynamic efficiency, C_l/C_d, shown in Fig. 5.

The comparison of the C_p distribution of three different excitation frequencies in Fig. 4 illustrates that the only effective frequency for the current geometry and operating conditions is at $F+ = 1.0$. Excitation of the baseline flow with $F+ = 1.0$ results in an improvement on the C_p distribution on the suction surface of the aerofoil. The sound waves introduced at the frequency of unsteady disturbances present in the shear layer, excites the natural disturbances in the shear layer, which results in earlier transition of the shear layer followed by improved vortex coherence in near wall regions of the separated flow over the suction surface compared to the baseline flow. The shedding of more coherent vortices downstream transfers energy to the low momentum separated flow in the suction surface near wall region that results in local flow reattachments. These local flow reattachments and their interactions with separation region

of aerofoil suction surface is revealed in C_f distribution as illustrated in Fig. 4. Local flow reattachment is more pronounced in between $x/c = 0.7 - 0.85$ with $F+ = 1.0$ excitation. In the case of $F+ = 0.5$ and $F+ = 2.0$ excitation frequencies, there is almost no effect of excitation on C_p distribution whereas the effect on C_f appears as weak local interactions of the separated flow with the aerofoil suction surface, showing no major effect of acoustic excitation for the harmonic frequencies considered.

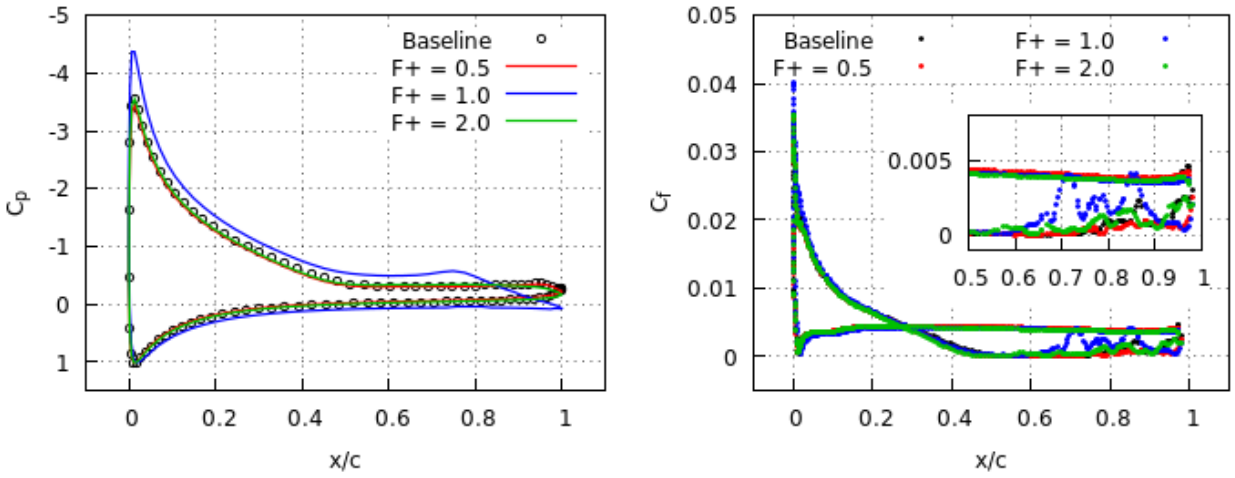


Fig. 4 Effect of acoustic excitation frequency on time- and span-averaged C_p and C_f at $A_m = 1.8\%$.

The effect of acoustic excitation on aerodynamic performance is assessed in Fig. 5 in terms of percent change ig C_l/C_d compared to the uncontrolled flow for each of the acoustic excitation frequencies considered. Excitation of baseline flow with the frequency of natural disturbances, $F+ = 1.0$, present in the shear layer provides 42.9% increase in overall C_l/C_d of the aerofoil whereas exciting the flow with the first sub-harmonic and the first harmonic of natural frequency does not provide any considerable improvement. Fig. 5 indicates that acoustic excitation can provide a significant aerodynamic performance improvement in near-stall angle-of-attacks when applied at a certain effective frequency, which is the natural frequency of the separated shear layer for the flow an aerofoil examined in the current work.

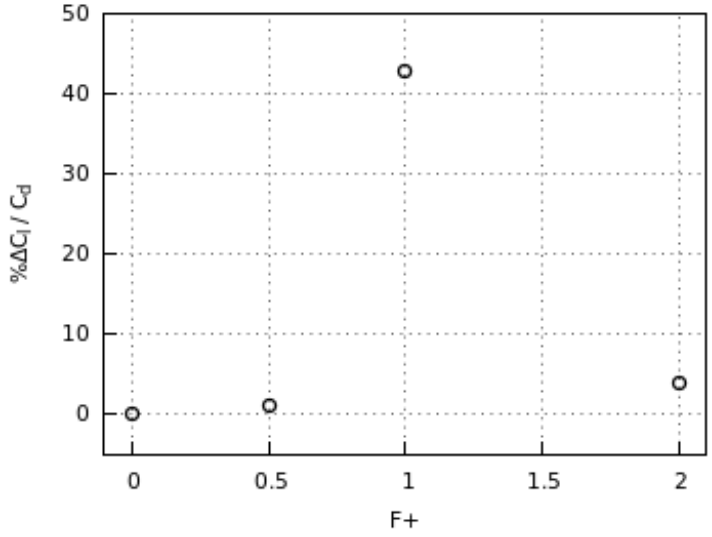


Fig. 5 Percent change in C_l/C_d with respect to $F+$ at $A_m = 1.8\%$.

The effect of acoustic excitation frequency on the separated flow field over the NACA0015 aerofoil is investigated by 8 equal intervals of a single period of the flow with normalized spanwise vorticity superposed on instantaneous velocity field. Natural frequency of the separated shear layer is used for the calculation of the period of uncontrolled flow whilst the excitation frequency is utilized for each excited flow. The corresponding time intervals are $\Delta t = 0.000357s$ for uncontrolled flow, $\Delta t = 0.000357s$ for $F+ = 1.0$, $\Delta t = 0.000714s$ for $F+ = 0.5$ and $\Delta t = 0.0001785s$ for $F+ = 2.0$. Excitation with $F+ = 1.0$ organizes the vortical structures in the vicinity of the suction surface in such a way that shedding of coherent vortices is promoted in the separated flow. Acoustic excitation with $F+ = 1.0$ also results in an earlier transition within the shear layer that results in earlier shear layer roll up and closer shear layer to the aerofoil suction surface compared to the uncontrolled flow as seen in Fig. 6. The closer shear layer to the aerofoil surface accompanied by enhanced vortex coherence is more profound that results in an improved turbulent mixing and hence local flow reattachments due to the energy transfer to near wall low momentum separated flow in the uncontrolled flow.

Excitation with the first sub-harmonic and the first harmonic frequencies does not result in any considerable flow separation suppression in this case. Although excitation with $F+ = 0.5$ and $F+ = 2.0$ reorganizes the vortex roll-up and shedding in the uncontrolled flow, vortex coherence is not observed in the near wall region of flow separation. Therefore, excitation with these frequencies does not improve the flow separation characteristics reasonably. However, excitation with first harmonic frequencies promotes vortex coherence in the wake of the aerofoil. In overall, the frequency of natural disturbances present in the uncontrolled flow has been found to be the optimum excitation frequency among the frequencies considered in this work. It is to be noted that a range of frequencies around $F+ = 1.0$ is expected to be effective although other frequencies in this range may present relatively lower effectiveness. The number of excitation frequencies considered has been limited to three frequencies due to the limitations on computational resources available. Further investigations on the range of effective frequencies remains as a future work.

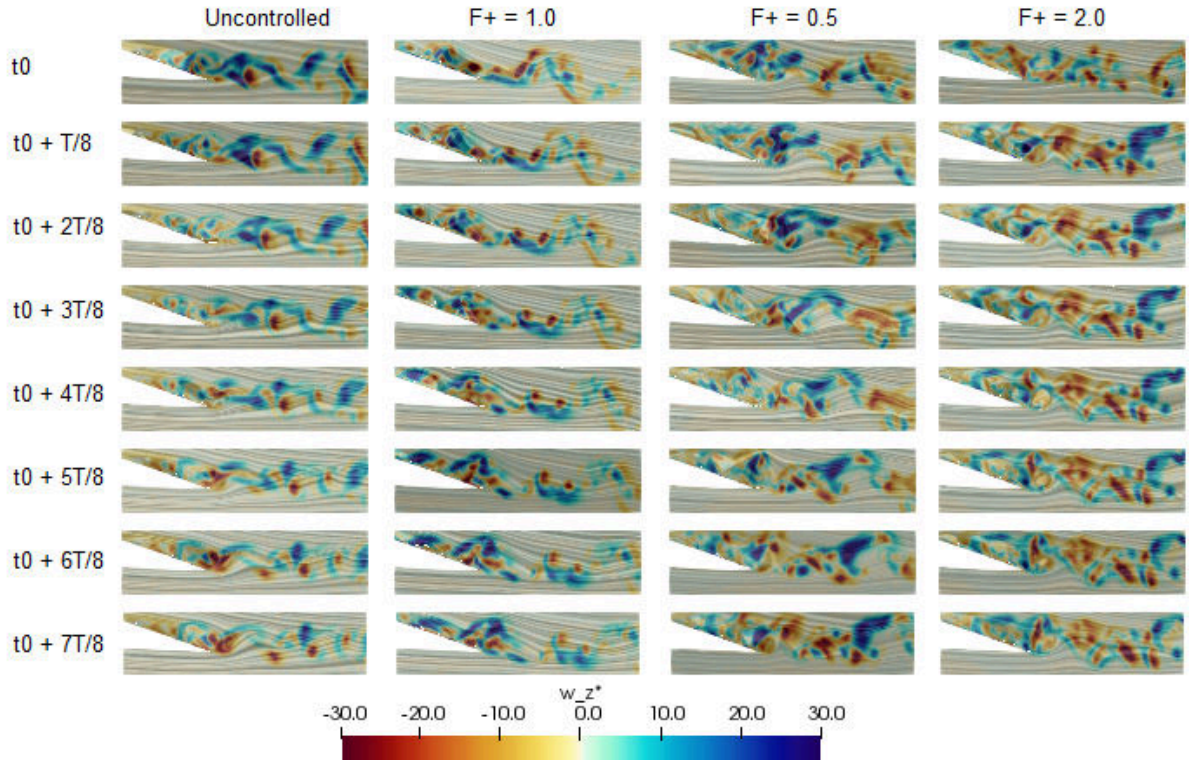


Fig. 6 Normalized spanwise vorticity contours superposed on instantaneous velocity field; effect of acoustic excitation frequency.

C. Effect of Excitation Amplitude

Another important parameter in acoustic excitation is the amplitude of excitation, A_m, which is quantified in percentages of the free stream velocity magnitude. Amplitude of excitation is varied from $A_m = 1\%$ to $A_m = 10\%$ at a constant excitation frequency $F+ = 1$ and the effect of excitation amplitude on time and span averaged pressure coefficient, C_p and skin friction coefficient, C_f, are shown in Fig. 7. As the excitation amplitude is increased further up to $A_m = 10\%$, a gradual advancement of transition and reattachment locations upstream on the suction surface is observed while the boundary layer separation is shifted further downstream. The effect of excitation amplitude on advancement of local reattachment locations can be observed on local pikes in C_f plot in Fig. 7. It has also been observed that there is an optimum excitation amplitude threshold beyond which transition, separation and reattachment locations converge to a level which implies there is a maximum effective excitation amplitude. The improvement gained by the acoustic excitation is not beyond the maximum aerodynamic efficiency point of the aerofoil.

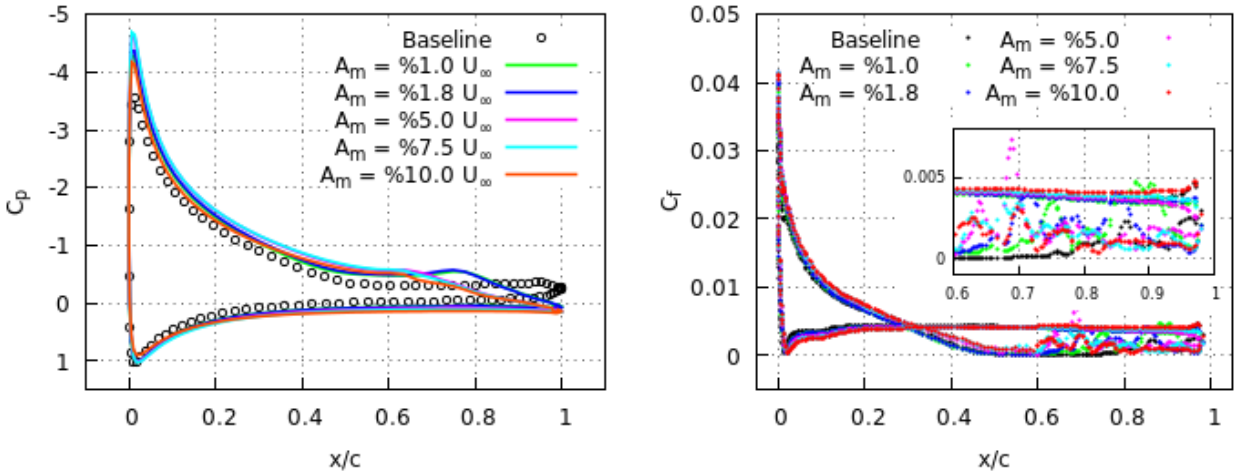


Fig. 7 Effect of acoustic excitation amplitude on time and span averaged C_p and C_f at $F+ = 1$.

The effect of acoustic excitation amplitude on transition, separation and reattachment locations is further quantified in Table 1. The point of separation is identified by a nearly constant pressure region in Fig. 7. The location of transition, on the other hand, is identified based on the onset of sudden pressure increase as the transition takes place over a range rather than a singular point. It has been observed that acoustic excitation promotes earlier transition, which leads to reattachment of the separated shear layer and a separation bubble over the suction surface is formed. The point of separation advances upstream with increasing excitation amplitude whilst separation point moves downstream over the aerofoil suction surface, resulting in a lower extent of the separation bubble. With acoustic excitation applied at $A_m = 1\%$, for example, transition of the separated boundary layer advances upstream by $1.83\%c$ compared to the uncontrolled flow whereas transition in separated boundary layer advances upstream by $14.76\%c$, which is followed by flow reattachment at around $x/c = 0.775$. As with increasing excitation amplitude, point of separation is continuously moved downstream up to the $x/c = 0.6$ for $A_m = 7.5\%$, resulting a lower extent of separation bubble. It is also observed that increasing excitation amplitude beyond $A_m = 5\%$ does not provide any further improvement in point of separation and transition whereas point of reattachment is still moved upstream.

$[x/c]$	*Uncontrolled*	$A_m = 1\%$	$A_m = 1.8\%$	$A_m = 5\%$	$A_m = 7.5\%$	$A_m = 10\%$
Separation	0.546	0.556	0.573	0.599	0.600	0.594
Transition	0.745	0.635	0.605	0.605	0.604	0.603
Reattachment	–	0.775	0.749	0.693	0.606	0.636

Table 1 Effect of excitation amplitude on aerofoil suction surface separation, transition and reattachment points, shown in percents of chord length .

The effect of acoustic excitation amplitude on aerofoil performance is quantified based on C_l/C_d, shown in Fig. 8. It has been observed that even the lowest excitation amplitude considered, $A_m = 1\%$ improves aerofoil aerodynamic performance by 33.4%, which shows that $A_m = 1\%$ is above the minimum threshold excitation amplitude that makes the acoustic excitation effective. Increasing excitation amplitude results in an asymptotical increase in C_l/C_d up to $A_m = 5\%$ at which significant reattachment of separated boundary layer is achieved, forming a separation bubble in agreement with the observations in Fig. 7 and Table 1. Further increase of excitation amplitude has a minor effect on aerodynamic performance. Therefore, it is concluded that $A_m = 5\%$ is the optimum excitation amplitude for the current aerofoil profile under specified operating conditions.

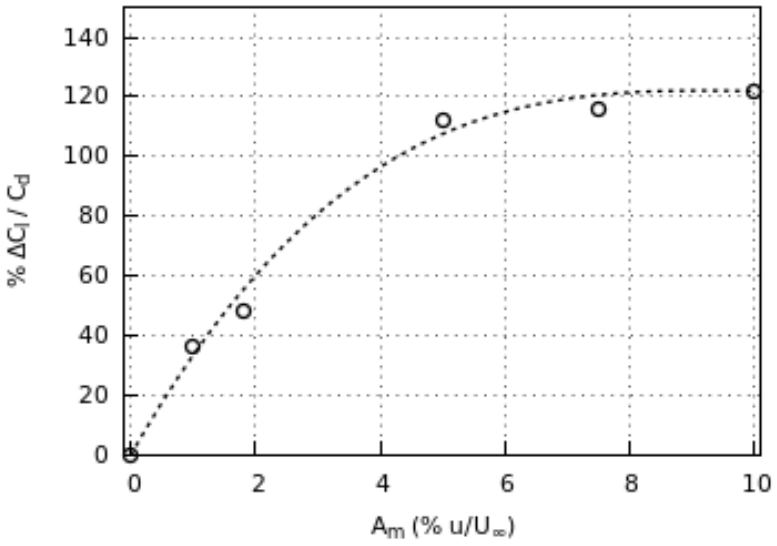


Fig. 8 Percent change in C_l/C_d with respect to A_m at $F+ = 1$.

The effect of excitation amplitude on flow separation characteristics over NACA0015 aerofoil is investigated in terms of normalized spanwise vorticity superposed on instantaneous velocity field over a period of excitation in Fig. 9 with time intervals $\Delta t = 0.000357s$ for the excitation frequency $F+ = 1.0$. As the flow starts to be excited by sound waves with $A_m = 1\%$, shear layer roll up is observed to shift upstream, with an accompanied movement of the separated shear layer closer to the suction surface of aerofoil. With further increment of excitation amplitude to $A_m = 1.8\%$ results in substantial enhancement in vortex coherence that transfers energy to the near wall separation region, resulting in local flow reattachments as shown in Fig. 9. Excitation of the uncontrolled flow with $A_m = 5\%$ has a major effect on flow separation characteristics that the onset of transition is shifted upstream considerably. The earlier transition of the separated shear layer triggers vortex roll up and reattachment of the shear layer eventually, forming a separation bubble. The extent of separation bubble covers relatively smaller portion of the aerofoil chord compared to the uncontrolled flow and smaller excitation amplitudes compared so far. These changes in flow separation characteristics arises as improvements in aerodynamic performance supporting the previous findings in Fig. 7 and 8. Further increase of excitation amplitude from $A_m = 5\%$ has only a minor effect on flow separation characteristics as the flow is significantly attached. However, it should be noted that excitation with $A_m = 5\%$ results in significant reduction of the wake accompanied by substantially more coherent vortex structures in the flow compared to the other excitation amplitudes and uncontrolled flow. When the excitation amplitude is further increased to $A_m = 10\%$, relatively larger vortices appear with a reduced coherence.

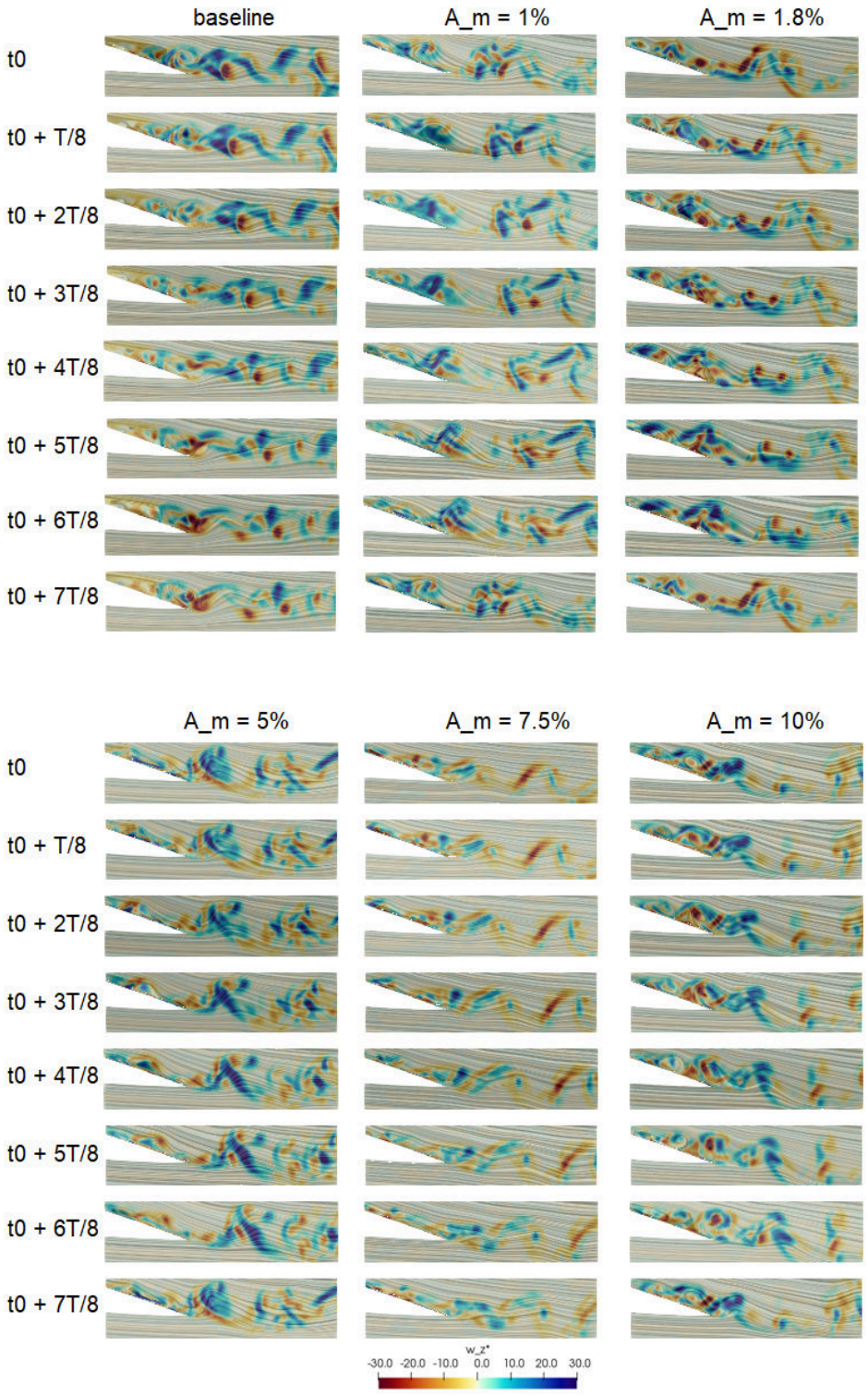


Fig. 9 Normalized spanwise vorticity contours superposed on instantaneous velocity field; effect of acoustic excitation amplitude at $F+ = 1.0$.

V. Conclusions

Numerical modelling of flow separation control via acoustic excitation over NACA0015 aerofoil at $Re_c = 1.0\,x10^6$ is conducted at a pre-stall angle-of-attack of $\alpha = 11°$. Improved Delayed Detached Eddy Simulation (IDDES) is used in numerical analyses. It has been shown that the IDDES model can reasonably capture the unsteady characteristics as well as turbulent scales in the uncontrolled flow field. Therefore, it is suitable for flow control applications including acoustic excitation.

The main focus of this study is the investigation of the effects of acoustic excitation frequency and amplitude on flow separation over NACA0015 aerofoil at a near-stall angle-of-attack. It has been observed that acoustic excitation can dramatically suppress flow separation when applied under certain excitation parameters, i.e. excitation frequency and amplitude. The effective excitation frequency has been obtained as the frequency of the most amplified disturbances in the uncontrolled flow field. Excitation with $F+ = 1.0$ reorganizes the shear layer roll up and vortex shedding characteristics of the uncontrolled flow such that the point of separation is shifted downstream whereas the onset of transition is advanced upstream, promoting flow reattachment over the suction surface of aerofoil. The excitation with harmonics of the natural frequency has negligible performance improvements. Excitation amplitude, on the other hand, has a significant effect on the flow field when applied at the natural frequency of the most amplified disturbances in the uncontrolled flow. Transition of the separated shear layer is promoted when the baseline flow is excited even with the lowest excitation amplitude, $A_m = 1\%\ \Delta u/U_\infty$, considered in the present work. It has been quantitatively shown that the point of separation shifts downstream over the aerofoil whilst the onset of transition and the region of reattachment advance upstream over the suction surface with increasing excitation amplitude. There is, however, a threshold excitation amplitude beyond which excitation of separated flow does not provide any considerable improvement on flow separation characteristics and hence the aerofoil performance.

It has been shown in the present work that the effect of acoustic excitation on flow separation over a NACA0015 aerofoil operating at near-stall angle-of-attacks and moderate Reynolds numbers can be predicted by use IDDES method. More detailed investigations of the effective excitation frequency and amplitude remain as a future work.

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Coskun, Seyfettin; Pachidis, Vassilios; Ubulom, Iroizan; Bacic, Marko

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