Trailing-Edge Noise Reduction via Spanwise Oscillation

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Summary To reduce trailing-edge noise the turbulent boundary layer is actively modified. First, the impact of a theoretical damping force and second, a spanwisely varying fluid injection are numerically analyzed.

Introduction

Trailing-edge noise is generated by a turbulent flow field which undergoes an abrupt change regarding the boundary condition. When the flow characteristics changes from a wall-bounded to a free-shear layer flow, strong broadband radiation occurs due to acoustic scattering. Theories of Chase [1] and Howe [2] are based on the turbulent source scattering. When high wavenumber turbulent components flow over the trailing edge, relatively long wavelength acoustics is radiated. To clarify the sound mechanism Amiet [3,4] considered the convecting surface pressure spectrum as a proper source. Howe [2,5] used Lighthill's acoustic analogy to introduce a sound generation model determined by eddy-convection velocity, spanwise coherence function, and Mach number. From the findings discussed in the aforementioned literature it can be concluded a reduction of the noise generation requires a refined turbulence control to diminish the strong vortical flows inside the turbulent boundary layer approaching the trailing edge.

To ensure the aforementioned turbulence control to achieve a sufficient noise reduction the external impact on the flow field must have a temporal scale based on the bursting frequency of the turbulent boundary layer and a spatial scale based on the spanwise spacing of the streamwise streaks near the wall. That is, additional flow disturbances are introduced to weaken the turbulence generation involved in the acoustic radiation. First, a turbulence control over a flat plate is numerically investigated by using an additional damping force in the momentum equations [6] to show the achievable noise reduction with the control strategy. Next, a spanwise disturbance [7] is introduced to eliminate coherent structures near the wall. The detailed analysis will evidence the noise mechanism which is directly linked to the turbulent fluctuations adjacent to the wall.

Numerical Method

The governing equations of the flow field are the unsteady compressible Navier-Stokes equations which are solved by a finite-volume based large-eddy simulation (LES). The equations describing the sound propagation are the acoustic perturbation equations (APE) in the APE-4 formulation [8]. A detailed description of the two-step method including the discretization of the Navier-Stokes and the acoustic perturbation equations is given in [9].

Results

The LES for the flow over a flat plate is performed at a freestream Mach number Ma=0.6 and a Reynolds number of Re=17000 based on the boundary layer thickness δ_i at the inlet and the freestream velocity. First, the turbulence control to reduce the turbulence intensity near the wall is investigated by imposing an additional body force in the wall normal (v) and spanwise (w) components of the momentum equations [6] $-(\rho/\phi^{+})\,f(y^{+})[v,w]^{T}$ where the function $f(y^+)$ is defined in inner coordinates as $f(0 \le y^+ \le y^+_d)=1$ and $f(y^+ > y^+_d)=0$. The thickness of the damping layer is $y^+_d=60$ and the value of the temporal coefficient ϕ^+ is chosen to simulate a strong body force near the wall. In figure 1 the effect of the near-wall damping force is evidenced. The small scale vortices adjacent to the wall are completely suppressed and the large scale hairpin-like structures shown in the uncontrolled flow are not generated in the controlled flow.

Next, an injection method with a spanwise variation of the momentum flux is considered. The injection velocity *V(t,z)* is defined by the bursting period of turbulent boundary layer (T_b) and the spanwise spacing of small scale vortices near the wall (L_v) $V(t,z) = \varepsilon U_\infty \cos(at/T_b + bz/L_v)$ where ε defines the amplitude relative to the freestream speed (U_∞), *a* and *b* are control parameters for the injection frequency and wave number. To assess the impact on the near-wall flow structures two injection methods, injections by steady and spanwise varying momentum, are applied to a turbulent flat plate boundary layer.

The u-velocity contours based on the spanwise varying injection are compared with the steady injection in figure 2. The transversal disturbance is based on a high frequency of $10/T_b$ with a spanwise length scale of $2L^+_v$. The instantaneous contours show no regeneration of small scale vortices. This result indicates the spanwise transversal disturbance to effectively suppress the small scale vortices involved in regenerating turbulence near the wall. The detailed quantitative analysis of the flow field and the acoustic field at several flow configurations based on the proposed noise reduction technique will be discussed in the presentation.

References

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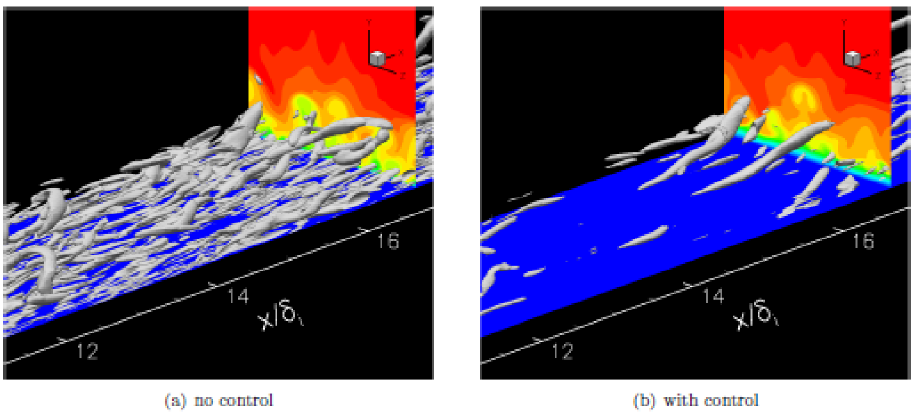

Figure 1. Instantaneous contours of the second invariant of velocity gradient tensor (a) without flow control, (b) with flow control near the wall at y+ ≤ 60.

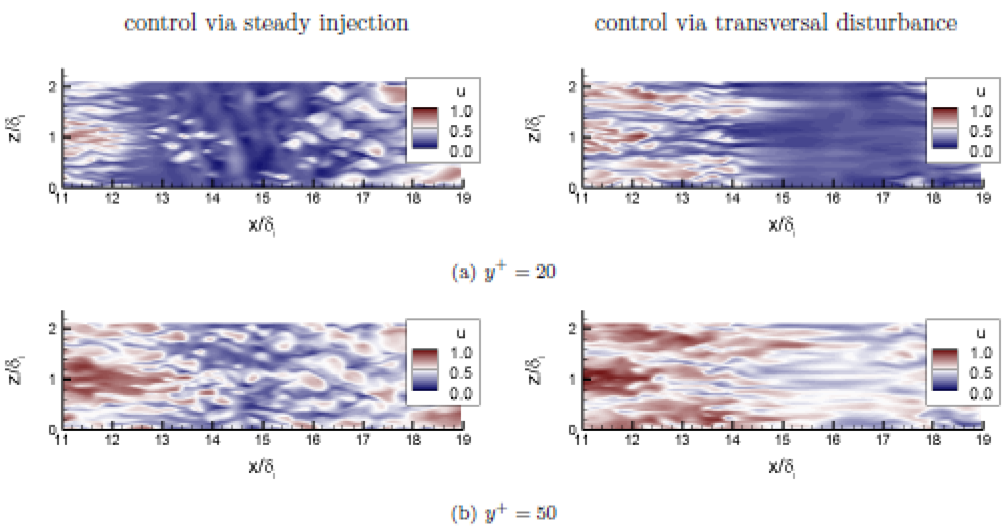

Figure 2: Contours of streamwise velocity component (u) at the wall normal distance (a) y+ = 20, (b) y+ = 50, left (control via steady injection), right (control via transversal disturbance).