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A numerical investigation of the airfoil-gust interaction noise in transonic flows: Acoustic processes

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ABSTRACT

The sound produced by airfoil-gust interaction is a significant source of broadband noise in turbofan engines or contra-rotating open rotors (CRORs). There are competing mechanisms in this regime because of the presence of shocks that were seldom considered in the previous subsonic studies. A numerical investigation of airfoil-gust interaction noise at transonic speeds is undertaken in this work. By introducing vortical gust/synthetic turbulence to specified regions in the computational domain to interact with different elements in the flow field, it is shown that the dominant sound source is caused by leading edge-gust interaction. It is demonstrated that both streamwise and transverse disturbances interact with the near-field non-uniform mean flow and shocks can produce sound using a local gust injection method. The propagation of sound is significantly influenced by the presence of the shocks, and the far field radiation pattern is changed. We also study the effect of gust strength on the near and far field properties. The linearity is maintained for gust strength smaller than 1.0% of the mean flow velocity. Otherwise, the shocks may experience oscillations that will alter the near-field aerodynamics and far-field radiation.

1. Introduction

With the growth of worldwide aviation, there are more stringent requirements to reduce the impact of aircraft operation on the environment, driving continuous research of aircraft designs. In particular, noise pollution is a severe problem that affects passengers and crew as well as the community on the ground. The aircraft noise consists of a complex set of sound sources that are mainly produced by unsteady, turbulent flows travelling through the propulsive systems and around major airframe components [1,2]. During the take-off and landing phases of the flight, the engines are the primary source of aircraft noise that contains both tonal and broadband components [3]. Leading edge noise due to the interaction between fan wakes, and the outlet guide vanes in the turbofan engines or aft rotor blades in contra-rotating open rotors is a significant broadband source. An efficient model of the leading edge noise prediction is based on Amite's analytical solution that makes assumptions of flat plate geometry, zero angles of attack (AoA) and uniform background flow [4,5]. However, in practical applications, there are real factors that can influence the accuracy of the analytical prediction such as the blade geometry, the turbulence stochastics, the background mean flow distribution and the cascade effect. It is desirable to study the implications of these factor in real applications.

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As for the impact of airfoil thickness, Paterson and Amiet measured the noise generated by an NACA0012 airfoil in a homogeneous, isotropic turbulent flow [6]. It was found that the flat plate model [4] predicted the sound generation well for the low-frequency component while discrepancies (nearly 5 dB noise reduction compared with the flat plate solution) appear for small wavelength gusts. Olsen and Wagner [7] measured three thickness-to-chord airfoils (3%, 13% and 37%), and showed that the noise is reduced with increasing thickness, and there is more reduction for high-frequency components. By testing several airfoils of different chord length and thickness, Devenport et al. [8] also discovered the noise reduction due to the airfoil thickness. This conclusion was also confirmed in other experimental studies, e.g. Oerlemans and Migliore [9] and Roger and Moreau [10]. Additionally, Chaitanya et al. [11] measured the noise reduction of an NACA0012 airfoil (compared against the flat plate solution [4]) at different flow speeds, and found that the noise reduction varies with Mach number. As for the numerical aspect, Atassi et al. [12], Scott and Atassi [13], Lockard and Morris [14], Gill et al. [15], and Gea-Aguilera et al. [16] conducted simulations to study the thickness effect by injecting divergence-free vortical disturbances into the computational domain. It is showed that the airfoil thickness could alter the unsteady airfoil response because of the mean flow distortion for both single frequency and broadband simulations.

The airfoil AoA has a strong effect on the pressure response function (for a single frequency component), but the difference can be small when the airfoil is impacted by isotropic turbulence. Experiments have been conducted to address this issue, and it was found that the impact of airfoil AoA is less significant than the airfoil thickness [6,9,17,18]. Devenport et al. [8] conducted a systematic measurement of the leading edge noise of an NACA0012 airfoil with the AoA ranging from 0° to 12°, and found the difference between the sound pressure levels (SPL) is smaller than 1.0 dB. Similar conclusion was conducted in the experimental work by Roger et al. [10] and Moreau et al. [17]. The inefficient effect of the airfoil AoA and camber to leading edge noise were also confirmed by the numerical study of Gill et al. [15]. As for the effect of the background flow, Lockard and Morris [14] conducted simulations about airfoil-harmonic gust interaction by solving both Euler and Navier-Stokes equations, showing that the fluid viscosity is relatively unimportant. Similar conclusions were also given by Atassi et al. [19]. Additionally, Gill [20] and Hainaut et al. [21] compared linearised Euler equations (LEE) simulation results using different background flows. A uniform mean flow is not recommended since many important physical impacts, e.g. the gust distortion by non-uniform mean flow [15], are not accounted for. By contrast, both inviscid and viscid background fields could yield similar results for relatively high Mach number flows [20].

The studies above were conducted in subsonic flows, and it is unclear if there are similar effects at higher speeds. In real configurations where leading edge noise can appear, such as on the aft blade of an open rotor, locally supersonic flows might occur at both blade tips and hubs [20,22,23]. The presence of shocks brings new challenges to the problem of studying the acoustic processes. To identify the property of each of the competing mechanisms, a plenty of previous investigations focused on the turbulence/gust-shock interaction, by using either analytical solution [24–27] or numerical simulations [28–30] for instance. The normal shocks were assumed, and the amplification of the turbulence strength, the sound generation due to the interaction were observed. Evers [31] and Evers and Peake [32] made extensions to account for the realistic geometry and the strength of shocks using a small disturbance theory for a thin airfoil and predicted the sound production in the downstream direction. The presence of shocks makes the acoustic problems complicated: (i) the sound is generated by the airfoil leading edge-gust interaction, and it can be scattered by the shocks and refracted by the near field mean flows; (ii) the distortion of gusts in the supersonic flow can lead to additional sound generation; (iii) there might be shock oscillations when interacting with the oncoming turbulence, and this motion can potentially affect the sound field; (iv) the interferences amongst various flow and acoustic elements/features can alter the sound distribution. In previous work by the authors [33], numerical simulations about the acoustic response of airfoils being subjected to harmonic gusts in transonic flows were conducted. There are multiple well-defined acoustic radiation peaks and troughs in the upstream direction whenever there are shocks. Moreover, the effect due to the presence of shock waves can be significant even for low-frequency gusts. However, the exact cause of the changes in the upstream sound directivity was unknown. In those simulations, all acoustic related processes were coupled since the harmonic gusts were injected across the entire computational domain.

In this work, numerical simulations are conducted to address the aforementioned acoustic processes in transonic flows. A local gust ingestion method is developed to introduce the harmonic gust in thinly striped regions to study the sound generation at the leading edge and in the supersonic flows separately. In a desired upstream transverse location, the value of the velocity fluctuation is expressed by the conventional harmonic gusts, while it gradually vanishes to zero in the remaining parts of the computational domain. Also, simulations using an advanced synthetic turbulence method based on the digital filter [16] approach are conducted. The turbulences are introduced in different regions of the computational domain, and the broadband response of different elements in the fluid field is evaluated. As for sound production due to shock oscillation, it can be expected that this effect is negligible for oncoming gusts with small amplitude. Therefore, simulations of gusts with variable amplitudes are conducted to explore the limit when this effect becomes significant. Additionally, it is known that the blockage of leading edge to oncoming vortical gust can result in unsteady pressure distribution along the airfoil surface [34], leading to dipole patterned radiation of the leading edge noise. Pure acoustic dipoles are therefore introduced into the computational domain to mimic the sound produced by the airfoil leading edge-gust interaction, and to study the effect of shocks on the sound propagation. The pure dipole simulations are not used for accurate prediction since the amplitude and phase vary along the airfoil surface as distributed dipoles [4], while the specific values are unknown for practical configurations.