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Effect of an excrescence in the slat cove: Flow-field, acoustic radiation and coherent structures

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ABSTRACT

Slat noise during aircraft landing is already a barrier to the development of quieter commercial airplanes. Investigations have been made by several research groups to understand the mechanism of slat noise generation. Most of the published works related to slat noise consider clean idealized geometries, whereas real slats contain some imperfections to enable its operation. The influence of a protrusion on the slat cavity surface on the unsteady flow around the slat and on the propagated sound was here investigated via numerical simulations. The protrusion models a sealing device designed to avoid metal–metal contact. A commercial code based on the Lattice-Boltzmann method was used to compute the unsteady flow. The far-field acoustic propagation was calculated by means of the Ffowcs Williams–Hawkings analogy and the Proper Orthogonal Decomposition (POD) was used to investigate the dynamics of the cove flow. The effect of the seal on the time-averaged pressure distribution is limited to the region close to it. However, tonal peaks in the noise radiated from the slat region are significantly higher when the seal is introduced. The present results show that, at the frequency of one of the tonal peaks, pressure fluctuations outside the cove are highly correlated with large-scale structures in the cove mixing-layer and at its impingement on the slat lower surface. The results also show that the introduction of the seal increases the coherence of these structures.

1. Introduction

In the last decades, aircraft engines have undergone many advances in noise reduction, such as the use of high by-pass turbofans, acoustic liners and noise-suppression nozzle shapes. This fact, summed to the low-thrust conditions applied on engines during the landing phase, brings airframe noise as one of the most important noise sources during this flight phase [9]. Among the airframe noise sources, the most important components are the landing gear, flap-side edges and the slat. The importance of the slat as a noise source is highlighted by the fact that it is distributed along almost the whole wing span.

A number of experiments carried out to study slat noise generation and radiation have been published [8,9,17,18], making it possible to separate the slat noise into three main components: a high frequency tone, a broadband noise at low and medium frequencies and a series of tonal peaks overlapped to the low-medium frequency broadband noise. Both experimental [8,18] and numerical [19,32] works studied the tonal high-frequency peak and its generation is attributed to the vortex shedding from the slat trailing edge. However, this noise component is found only on models [9], given the constructive restrictions to build trailing edges as thin as the scaled model would require. Experiments [10,11] have actually shown that the broadband spectrum is the only noise component found in full-scale models, attributing the multiple tonal peaks to the low Reynolds number of wind-tunnel experiments. Their generation is not fully understood but some theories based on Rossiter [25] or Parker [9] modes are proposed.

Along with the above experiments, 2D simulations were carried out [7,20,22,23] aiming at better understanding the unsteady behavior of the flow in the slat cove region. Two companion works [18,20] used PIV images to assess the accuracy of unsteady flow solutions produced by 2D computational simulation. The computational averaged velocity field compared well with experiments but the numerical calculation resulted in substantially larger spanwise vortices than the vortices observed in PIV images of slat cove. The

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use of a three-dimensional domain with an extruded airfoil [6,16] achieved better agreement with PIV measurements for the instantaneous spanwise vorticity field in the slat cove. This indicated the need to consider three-dimensional phenomena to properly simulate the flow structures in the slat cove. Time-accurate 3D simulations were carried out using the Lattice-Boltzmann formulation and compared with results based on Navier–Stokes calculations. Good agreement for the instantaneous spanwise vorticity field was achieved as well as for the near-field spectra [1]. Based on the observation that different slat boundary layer solutions did not result into significant changes in the noise generated, a model considering free-slip boundary condition on the slat surface was proposed [31]. This approach allows more efficient simulations, since the restriction of a maximum value for y^+ close to the wall is eliminated.

Correlation techniques are often an useful approach in order to shed light on the physics involved in noise generation and propagation, provided that enough experimental or simulation data is available. Examples of techniques that can contribute to the understanding of slat noise include cross-correlations in space and/or time, cross-spectra in frequency domain and stochastic estimation, to mention a few. A common feature of these methods is that, based on experimental or numerical realizations of a selected set of variables, they deliver relations existing between these variables without necessarily implying causal relations. Hence some previous insight in the process under consideration is advised. Very successful examples exist in the literature on the use of correlation techniques in unveiling the underlying physics; of especial interest here is Proper Orthogonal Decomposition (POD), the utility of which in the eduction of large-scale coherent structures in turbulent flows has been widely demonstrated [15].

Most of the simulations aiming at studying the flow around the slat and its noise consider idealized clean geometries. Nevertheless the slats installed in actual airplanes possess several small elements in the cove region. Such geometrical details include slat deflection mechanisms, anti-icing tubes and seals. These elements can change notably the flow dynamics and therefore the characteristics of the propagated noise. Two-dimensional simulations were carried out to assess the effect of different blade seal configurations on the slat noise [21], showing that an extended seal at the slat cusp reduces the amplitude of the radiated noise. Another element included in the geometry of those simulations [21] was a seal at the inner wall of the slat, that prevents the metal–metal friction between the slat lower surface and the main element upper surface and closes the space between the two elements in cruise configuration. However, 2D simulations showed no difference in the noise signature between the configurations with and without this latter seal. On the other hand, three-dimensional Lattice-Boltzmann simulations showed that, depending on the position, the seal can significantly increase the amplitude of the low-frequency tonal peaks [2].

The work described here analyses the consequences of a seal positioned at the slat cove on both the flow-field and the acoustic far-field considering three-dimensional simulations. The coherent structures inside the cove are analyzed using the correlation technique named Proper Orthogonal Decomposition.

2. Lattice-Boltzmann simulation of a high-lift airfoil

2.1. High-lift geometry

The present simulations use the MD 30P30N airfoil as baseline geometry. This high-lift airfoil has been extensively studied by NASA [6,18,23,24,28,29]. Some characteristics of this airfoil are presented in Table 1. The slat and flap chords are, respectively, 15% and 30% of the airfoil stowed chord ($c_{stowed} = 0.457$ m, in the present simulations). In the simulations, the trailing edges of the airfoil end in a sharp cusp, except the slat trailing edge that has a finite thickness of 0.092% of c_{stowed}. The computational mesh was not sufficiently refined in the trailing edge region to capture the slat vortex shedding.

Table 1
MD 30P30N geometry parameters.

	Deflection (°)	Gap (%)	Overhang (%)
Slat	30	2.95	−2.50
Flap	30	1.27	0.25

Besides the original geometry of the MD 30P30N airfoil, a variation of it is simulated with a small seal on the surface of the slat cove to model a device that avoids metal–metal contact when the wing is in cruise configuration. The seal is placed at a geodesical distance $d = 0.03c_{stowed}$ from the slat trailing edge (see Fig. 1 for the definition of d) which is equal to twice the distance between the reattachment point and the trailing edge. The height of the seal that intrudes the flow is three times the thickness of the slat trailing edge. This seal configuration corresponds to Case 1 in the numerical analysis by Bandle et al. [2]. We chose it because, among the configurations tested by them, this one resulted in the greatest increase of the slat noise, comparing to the original, clean slat geometry.

2.2. Lattice-Boltzmann method

The simulations described in this paper are computed using the commercial code PowerFLOW 4.3a. This code is based on the Lattice-Boltzmann method (LBM) that solves the discrete Boltzmann equation for the probability density function:

$$f(\vec{r} + \vec{c}\delta t, \vec{c}, t + \delta t) - f(\vec{r}, \vec{c}, t) = \Omega(f). \tag{1}$$

The function $f(\vec{r}, \vec{c}, t)$ represents the odds to find a particle in the position $\vec{r}$ with velocity $\vec{c}$ at an instant t. The term Ω is called collision term and represents the exchange of momentum between the particles. For the flow conditions of interest to aeronautics, this term can be properly approximated by [3]:

$$\Omega(f) = -\frac{1}{\tau}\left(f - f^{eq}\right) \tag{2}$$

where τ is a relaxation time and f^{eq} is the equilibrium probability density function. The Boltzmann equation is discretized in a Cartesian mesh and solved explicitly in a volumetric formulation that enables the solution of problems with complex geometries [5]. The zeroth and first moments give the density and velocity respectively. The compatibility of this formulation with the Navier–Stokes equation can be demonstrated by a Chapman–Enskog expansion [27].

To calculate the effect of subgrid turbulence scales, the code uses a modified version of the k–ϵ turbulence model in its Renormalization Group (RNG) form. In the modified k–ϵ RNG the factor η, that stands for the dimensionless strain rate in the original model, includes also the dimensionless vorticity, so that it becomes $\eta = |S|k/\epsilon + |\omega|k/\epsilon$. The modified model allows large-scale structures to be resolved by the Lattice-Boltzmann method [13].

The calculation of the sound propagated to the far-field is made by means of the Farassat's formulation [12] of the Ffowcs Williams–Hawkings analogy [4]. The surface of integration of the Ffowcs Williams–Hawkings method corresponds to the slat surface and the surface of the aft half part of the main element. Tests were carried out to show that, for the Mach number used, the quadrupole sources are negligible [28].

The simulation model is scaled to match the experiments from Jenkins et al. [18], resulting in a Reynolds number of 1.7 million